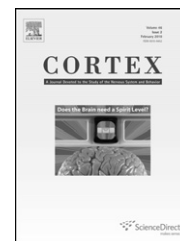




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Research report

Visual processing in pure alexia: A case study

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ABSTRACT

Whether pure alexia is a selective disorder that affects reading only, or if it reflects a more general visual disturbance, is highly debated. We have investigated the selectivity of visual deficits in a pure alexic patient (NN) using a combination of psychophysical measures, mathematical modelling and more standard experimental paradigms. NN's naming and categorization of line drawings were normal with regards to both errors and reaction times (RTs). Psychophysical experiments revealed that NN's recognition of single letters at fixation was clearly impaired, and recognition of single digits was also affected. His visual apprehension span was markedly reduced for letters and digits. His reduced visual processing capacity was also evident when reporting letters from words. In an object decision task with fragmented pictures, NN's performance was abnormal. Thus, even in a pure alexic patient with intact recognition of line drawings, we find evidence of a general visual deficit not selective to letters or words. This finding is important because it raises the possibility that other pure alexics might have similar non-selective impairments when tested thoroughly. We argue that the general visual deficit in NN can be accounted for in terms of inefficient build-up of sensory representations, and that this low level deficit can explain the pattern of spared and impaired abilities in this patient.

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1. Introduction

Pure alexia is an acquired disorder of reading characterised by slow and effortful reading of words and text. Patients with pure alexia usually show a linear relationship between the number of letters in a word and the time taken to read it, an effect known as the word length effect (WLE). Other language functions – including writing – are unaffected. Pure alexia can be distinguished from global alexia, where patients are completely unable to identify even single letters (Binder and Mohr, 1992; Leff et al., 2001). Also, although the terms pure alexia and letter-by-letter (LBL) reading are often used

interchangeably, they may refer to different entities. *Pure alexia* or *alexia without agraphia* refers to an acquired disorder of reading that leaves writing and other language functions intact. WLEs or LBL reading may be observed in patients suffering from other disorders (e.g., Price and Humphreys, 1992 for a discussion, see also Cumming et al., 2006). We use the term pure alexia to refer to a reading disorder in the absence of aphasia and agraphia, and this paper is concerned with theories of pure alexia, and not (necessarily) LBL reading.

Theories of pure alexia are usually divided into (i) alphabetical accounts, attributing the reading deficit to damage in a specialized system for word or letter processing, or the

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disconnection of this system from visual input (e.g., Cohen et al., 2004), and (ii) visual accounts, suggesting that a deficit that affects visual processing in general is at the core of the disorder (e.g., Behrmann et al., 1998a). As noted by Cumming et al. (2006; p. 1132) regarding these competing accounts, “the jury is still out because as yet relatively few studies of pure alexia have included adequate assessment of non-reading visual tasks”.

A classical view of pure alexia within cognitive neuropsychology is that it results from damage to a word form system, that “parses (multiply and in parallel) letter strings into ordered familiar units and characterizes these units visually” (Warrington and Shallice, 1980, p. 109). A more recent version of this hypothesis proposes that pure alexia arises after damage to an area in the left fusiform gyrus, often referred to as the visual word form area (VWFA), which is thought to be responsible for extracting abstract letter identities (Cohen et al., 2004). Most of the evidence for the existence of the VWFA comes from functional imaging studies of normal subjects, but so far there is little consensus regarding the existence of such an area, or which cognitive operations it may perform (e.g., Price and Devlin, 2003, 2004; Cohen and Dehaene, 2004; Starrfelt and Gerlach, 2007). There are some patient studies specifically addressing the selectivity of deficits after focal lesions in this particular brain region (Cohen et al., 2003; Hillis et al., 2005; Gaillard et al., 2006), but their results are inconsistent. The anatomical side of this question is beyond the scope of this paper, as our patient’s lesion extends beyond the putative VWFA, but the cognitive issue of the selectivity of pure alexia is addressed by comparing a pure alexic patient’s performance with letters, words, and digits, as well as objects.

Another main hypothesis suggests that pure alexia is the result of a deficit in processing many visual items in parallel (simultanagnosia) (Kinsbourne and Warrington, 1962; Farah, 1990). Indeed, pure alexia may even be referred to as *ventral simultanagnosia* (Duncan et al., 2003; Farah, 2004). Duncan et al. (2003) addressed the simultanagnosia hypothesis of pure alexia rather directly by using psychophysical measures and mathematical modelling – methods also employed in the present study. They found that their pure alexic patient did not have a severe problem with perception of multiple items as such, but showed decreased speed of processing even for single stimuli. Thus, a primary deficit in simultaneous perception did not seem to accurately describe the patient’s deficit. However, Duncan et al. (2003) only used letters as stimuli in their experiments. Given that their patient was alexic the results leave open the question of whether the reported pattern of deficits characterizes the patient’s visual perception in general. We try to overcome this limitation by measuring our patient’s processing speed and visual span of apprehension with two kinds of stimuli – letters and digits. Although letters and digits are similar symbols, number reading can be selectively spared in alexia with agraphia (Anderson et al., 1990; Starrfelt, 2007). Also, it is sometimes assumed that number reading can be spared in pure alexia, as reading of multidigit numbers in free vision has been reported to be preserved in some of these patients (Warrington and Shallice, 1980; Leff et al., 2001). Thus, as a first sensitive test of the selectivity of NN’s deficits, we compare his performance

with letters and digits in displays of single and multiple stimuli. Following a suggestion by Duncan et al. (2003), we also aim to test how the processing of letters within words may be affected by capacity limitations.

The third main account of pure alexia suggests that a general visual deficit is at the core of this disorder. Behrmann et al. (1998a) have shown that pure alexic patients’ object recognition abilities may depend on visual complexity, and that pure alexic patients show perceptual difficulties “under impoverished perceptual conditions where there is less support from organisational cues” (Sekuler and Behrmann, 1996, p. 968). They suggest that reading is one such impoverished condition, and therefore seems disproportionately affected. We address this question in the present study, by investigating NN’s picture recognition abilities both under normal and “impoverished” perceptual conditions.

2. Aims and methods

The theories of pure alexia predict different degrees of selectivity of impairments, and different patterns of performance with non-alphabetical stimuli. We test these predictions in a patient with pure alexia in two series of experiments.

First we compare the patient’s performance with letters and digits using a combination of psychophysical experiments and mathematical data modelling. The results are analysed in the framework of the Theory of Visual Attention (TVA: Bundesen, 1990) which enables performance on simple psychophysical tasks to be analysed into different functional components. The details of TVA are explained in Section 4.2.1. In this investigation we focus on two parameters of visual capacity: the capacity of visual short-term memory, K , and the speed of visual processing, C . The K parameter represents the ability to perceive multiple items in parallel (the apprehension span). The C parameter reflects the efficiency of visual recognition, which may be tested for different stimulus types, and by using displays of either multiple or single items. Variations in these parameters for letters and digits relate directly to main hypotheses of pure alexia: the alexia-simultanagnosia hypothesis would predict that K is impaired for all stimulus types, whereas C may be normal in single-stimulus situations. Instead, if a general visual recognition deficit underlies pure alexia, C for different object types should be affected also with single stimuli. Finally, if the problem is specific to letter perception, then C should be reduced for this particular stimulus type, but perception of other stimuli may be normal, including the ability to recognize multiple items at the same time (K). We also investigated our patient’s letter reporting ability in an experiment where both words and nonwords were used as stimuli, to test the hypothesis that patients with pure alexia perceive letters in words in the same (highly capacity limited) way that characterizes normal perception of unrelated items.

The second part of our investigation aims to characterize our patient’s performance with pictures. The tests with pictorial stimuli could not be conducted using the same TVA-based paradigms as the letter and digit experiments. Preliminary work in our lab suggests that capacity limits for line drawings are different from alphanumeric stimuli (Sørensen,

2007), and also more difficult to estimate reliably. Instead we used traditional error and reaction time (RT) measures for investigating object recognition. Accurate naming of visually presented objects has been reported in pure alexic patients (e.g., Gaillard et al., 2006), but to our knowledge this has never been reported with normal RTs. Thus, in the initial part of the investigation, we included a computerized object naming task, measuring both errors and RTs. Object recognition was further investigated by means of an object decision task with line drawings. We also included an object decision task with fragmented pictures, to test whether impoverished perceptual conditions would affect our patients' performance in this task.

3. Case report

3.1. Medical history

NN was 49 years at the time of this experimental investigation. He is a right-handed man (Edinburgh Handedness Inventory – EHI laterality quotient (LQ) = +100, Oldfield, 1971). Following thrombolysis-treatment of a lung-embolus on March 24th, 2005, NN suffered a cerebral haemorrhage affecting the posterior left hemisphere. A medullar haemorrhage occurred at the same time, causing a right side paresis, as well as left side paralysis of the lower extremity. Ophthalmological examination revealed no visual field deficit. The haematoma was evacuated on March 24th. An magnetic resonance imaging (MRI)-scan three days later showed three areas of abnormality in the brain substance: (i) infarction associated with haemorrhage in the right side of the medulla, centred on the pontomedullary junction. The lesion affects the dorsal brainstem more than the ventral part and is associated with local mass effect. (ii) A cortical infarction with associated haemorrhage affecting most of the left occipital lobe. The area of abnormality extends medially to include the striate cortex (V1) and laterally into the middle occipital gyrus (O2) but not into the lateral temporal lobe. The lingual gyrus is affected inferiorly as is the posterior and mid portion of the fusiform gyrus. The hippocampal and parahippocampal gyri are spared. (iii) A small area of abnormal signal in the anterior and dorsal part of the superior frontal gyrus relating to previous surgery for a meningioma. See Fig. 1 for illustration of the occipital lesion.

According to NN's medical records, neuropsychological assessment two months post injury revealed slow but correct reading of single words, while a few errors on word endings were noted in text reading. Writing of sentences, regular and irregular words, and nonwords were without errors. No problems were noted in naming to spelling. Slight problems with naming of line drawings were noted (Boston naming task: 49/60), as well as problems with fragmented visual material (Street completion test: 5/20). The neuropsychological records state that information uptake was reduced in the right visual field.¹ NN was in a rehabilitation programme at the Centre for Rehabilitation of Brain Injury in

Copenhagen, from October 2005 to March 2006, where he also participated in a two month project aiming specifically at training his reading ability. At the end of his rehabilitation programme, a thorough neuropsychological assessment of NN was conducted. The data from this evaluation are presented in Table 1. NN's performance was within the normal range compared to Danish norms, except for three scores on tests that involve psychomotor speed and alphanumerical material.

NN holds a doctorate in medicine. He has now returned to work as an MD, but works reduced hours and mostly performs routine work. His only remaining complaint is of reading difficulties, which affects his ability to read emails, books and newspapers. His paretic right arm affects his ability to write, but he is still able to write short messages both by hand and using a computer. Writing letters and prose poses a problem, as he finds it demanding to read what he has written.

3.2. Preliminary assessment

We first assessed NN's reading performance three months after his injury using a computerized reading test including 52 concrete nouns of 3–7 letters (see procedure details in Section 4.1.2). NN made no reading errors, and his mean RT was 2485 msec (standard deviation – SD = 1414). NN's WLE was 693 msec per letter [$r^2 = .563$, $F(1, 48) = 61.9$, $p < .001$]. The reading test was repeated in winter 2006, at which time NN's mean RT was 1973 msec (SD = 1642), and the WLE was 380 msec per letter [$r^2 = .130$, $F(1, 50) = 7.5$, $p < .01$]. We examined NN's visual fields using a perimetry program developed by Kasten et al. (1998, 1999). NN completely overlooked stimuli in the upper right quadrant. We also examined whether this visual field deficit was partial rather than absolute (cerebral amblyopia, cf. Habekost and Starrfelt, 2006), by repeating the test and instructing NN to direct his attention covertly, still with central fixation, to the impaired quadrant. This did not alter NN's performance; all but the most central stimuli in the upper right quadrant were overlooked, indicating that NN has an upper right quadrantanopia.

4. Experimental investigation

The experimental investigation reported here was conducted during March and April 2007. NN and the control subjects 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 (project no.: KF 01-258988).

NN was tested in three sessions of about 2 h each on separate days. A group of five age and education matched controls (three males), with no history of dyslexia, visual problems, psychiatric or neurological disease, completed the experiments in two sessions, on separate days. See Table 2 for control characteristics. To statistically analyze NN's performance compared to this control group, we used a test devised by Crawford and Garthwaite (2002a, 2002b). This test has proven highly robust for evaluating single-case results against control groups of limited size. Scores deviating more than 2.34 SD from the control group reached

¹ The reduced information uptake in the right visual field noted in the neuropsychological assessments at the hospital, can probably be ascribed to NN's visual field defect which was undiagnosed at this time.

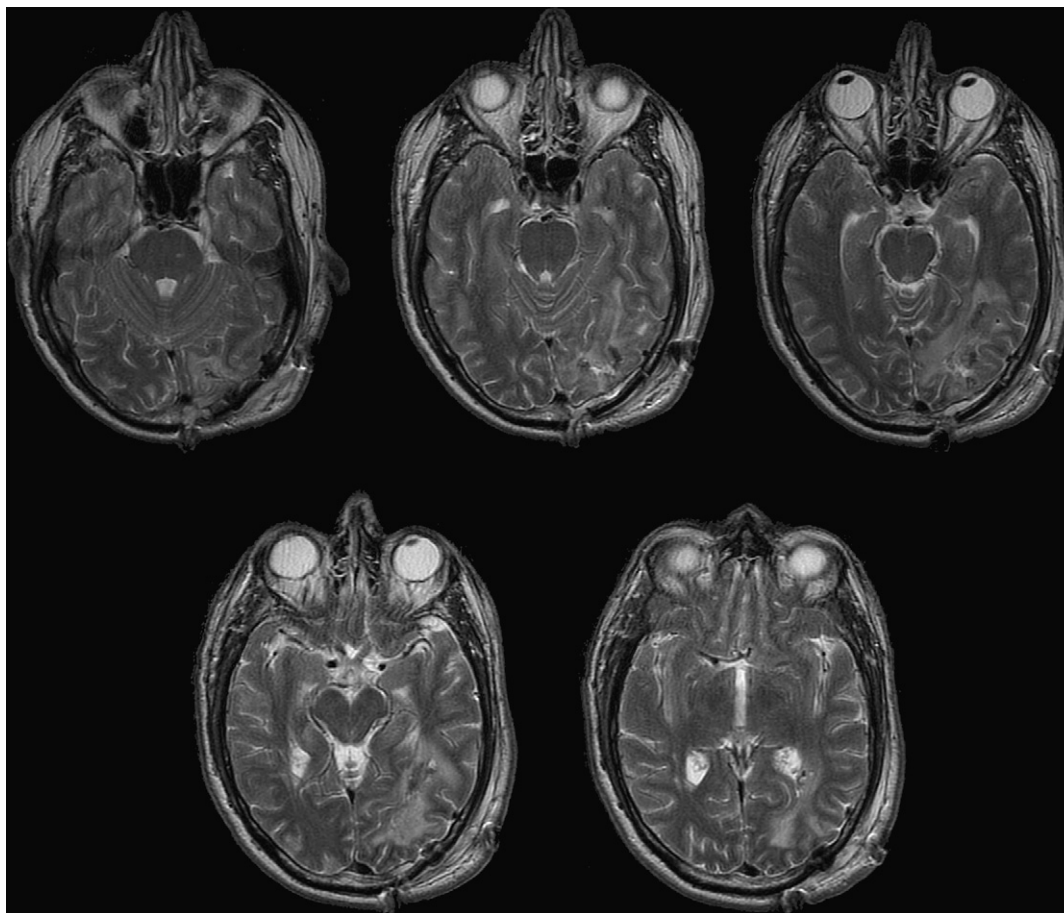


Fig. 1 – Axial view of T2 weighted MRI images showing NN's occipital lesion. The lesion includes striate cortex (V1), the middle occipital gyrus, the inferior part of the lingual gyrus, and the posterior and mid portion of the fusiform gyrus.

significance on this test (i.e., were classified as pathological). All p -values reported for comparisons between NN and the control group in the following are one-tailed and based on Crawford and Garthwaite's test, unless otherwise specified.

4.1. Background tests

4.1.1. Perimetry

We conducted a short computerized perimetry of 125 trials, using the perimetry program developed by Kasten et al. (1998, 1999) to test for luminance sensitivity. This revealed an upper right quadrantanopia with approximately 2.2° of foveal sparing.

4.1.2. Word reading

76 words from subtest 31 in the psycholinguistic assessments of language processing in aphasia (PALPA) battery (Kay et al., 1992, Danish version 2004) were presented centrally on a computer screen in 36 point Times New Roman (white letters on a black background), one at a time. RTs from word onset were measured with a voice key. Errors were recorded by the experimenter. The interval between response and presentation of the next stimulus was 2 sec. Subjects were instructed to read the words as quickly and accurately as

possible, and the initiation of a verbal response terminated the presentation of the words and triggered the voice key. A practice version with ten words was administered before the actual test.

Neither NN nor controls made any errors in this task. Four of NN's responses were excluded from analysis due to voice key errors, for the controls an average of 2.2 words (range 0–6) were excluded due to voice key error. NN's mean RT in this task was 1717 msec (SD = 748), significantly different from the control group mean of 482 msec (SD = 56) ($p < .001$). By linear regression, we estimated the slope of NN's WLE to be 271 msec per letter [$r^2 = .351$, $F(1, 70) = 37.8$, $p < .001$]. The mean effect of word length for the controls was 8.6 msec (SD = 7.6), and this effect was significant in two individual controls (WLEs for these two subjects were 14.7 msec and 19.6 msec, both $p < .001$). See Fig. 2 for a plot of the individual RTs by word length.

4.1.3. Auditory letter/digit span

We tested auditory span for up to five elements separately for letters (A–J) and digits (0–9). Sequences of 3–5 letters or digits (four sequences in each condition) were read out, and the subject was asked to repeat the presented sequence. The stimuli were presented approximately one per second, and the same item never appeared twice in the same sequence.

Table 1 – Raw scores in neuropsychological tests in March 2006 (provided by the Center for Rehabilitation of Brain Injury (in Copenhagen) – CRBI). Scores deviating more than 2 SDs from the mean of Danish norms are marked out with an asterisk (*). Two Wechsler Adult Intelligence Scale-Revised (WAIS-R) subtests (Information and Vocabulary) from the initial assessment at CRBI in October 2005 are also included, as they were not repeated at discharge.

Test	Raw score
Ravens Advanced Progressive Matrices – correct	10
Ravens Advanced Progressive Matrices – time	557 sec
WAIS-R Block design	27
WAIS-R Digit-symbol	41
WAIS-R Digit span	13
WAIS-R Information (2005)	27
WAIS-R Vocabulary (2005)	54
WMS-R Logical Memory 1 – learning	14,5
WMS-R Logical Memory 2 – learning	12
WMS-R Logical Memory 1 – retention	13
WMS-R Logical Memory 1 – retention	10
Luria's 10 words – retention	10
Rey's complex figure – copy	35
Rey's complex figure – retention (30 min)	17,5
Verbal fluency – animals	19
Verbal fluency – S-words	22
Trail Making A – time	43 sec*
Trail Making A – errors	0
Trail Making B – time	112 sec*
Trails Making B – errors	0
d2 – Total sum	271*
d2 – Errors	8

Maximum score in this test is 12 (4 sequences by 3 conditions). NN scored 12 in both the letter and digit task. The control mean score was 11.8 (range 11–12) for letters and 11.6 (range 11–12) for digits.

4.1.4. Visual processing – pictures

4.1.4.1. STREET COMPLETION TEST. The test was administered according to standardized instructions, where the pictures are presented for up to 10 sec with no time limit for responses. NN scored 13/20, which is within the normal range compared to Danish norms (Gade et al., 1988).

4.1.4.2. PICTURE NAMING. 40 black and white line drawings from the set of Snodgrass and Vanderwart (1980) were presented centrally on a computer screen. The pictures subtended 3–5° of visual angle. The pictures remained on screen until the subject made a response. The interval between response and presentation of the next stimulus was 2 sec. RTs from picture onset were measured with a voice key. A practice version with six pictures was administered before the actual task.

NN made one self-corrected error in this task. This item was excluded from the analysis, as were four other items due to voice key failure. NN's mean RT was 965 msec (SD = 300) which is not significantly different from a group of five controls (from Gerlach et al., 2005), for whom the mean RT was

Table 2 – Background data for NN and the mean for the control group (SDs in brackets). Education refers to years of schooling after primary education. Handedness was assessed with EHI (Oldfield, 1971), and visual acuity was measured using the Snellen chart while the participants were wearing their habitual glasses/contact lenses.

	Age	Education	Handedness	Visual acuity
NN	49	11	Right +100	6
Controls	51.4 (4.1)	10 (1.4)	Right +100 (0)	6.6 (1.2)

884 msec (SD = 61) ($p = .146$). There was no significant effect of visual complexity, as estimated using the norms provided by Snodgrass and Vanderwart (1980), on NN's RTs (Pearson's $R = .287$, $p = .089$).

4.1.5. Summary of background tests

At the time of the experimental investigation, NN had an upper right quadrantanopia, a visual field defect commonly seen in the context of pure alexia (Damasio and Damasio, 1983). He showed a WLE in single word reading with a slope of 270 msec per letter. This WLE is modest, but within the range reported for other patients with pure alexia (e.g., Behrmann et al., 1998b), and higher than generally reported for hemianopic alexia (e.g., Leff et al., 2006). NN's auditory letter and digit span was at least five items (more were not tested), which is on the same level as the control group results. NN performed within the normal range on the Street completion test, and his performance on a computerized picture naming task was comparable to normal controls. NN had earlier been shown to have no writing problems, and his pattern of performance is consistent with a diagnosis of pure alexia.

4.2. Processing capacity for letters and digits

4.2.1. TVA modelling

TVA is a mathematical model of visual processes (Bundesen, 1990; Bundesen et al., 2005) which assumes that all objects in the visual field compete for access to a short-term memory store. If a visual object is encoded into the store it is consciously recognized (and can be reported). The competition process is constrained by two capacity limitations: there is only room for very few (typically about four) visual objects in the short-term memory store, and there are also limited resources for sensory processing of the objects, corresponding to visual processing speed. Attention basically works by prioritizing these processing resources: the more resources that are allocated to an object, the faster it is processed, and the higher the probability that it ends up in visual short-term memory. TVA includes equations that model these processes by different functional components (parameters). The parameters can be estimated from performance on simple psychophysical tasks (e.g., single-stimulus report, whole report). Two parameters are particularly interesting for the purposes of the present investigation: the speed of visual processing, C , and the storage capacity of visual short-term memory, K . In addition the perceptual threshold t_0 is measured, but this parameter is of less theoretical relevance in the present context.

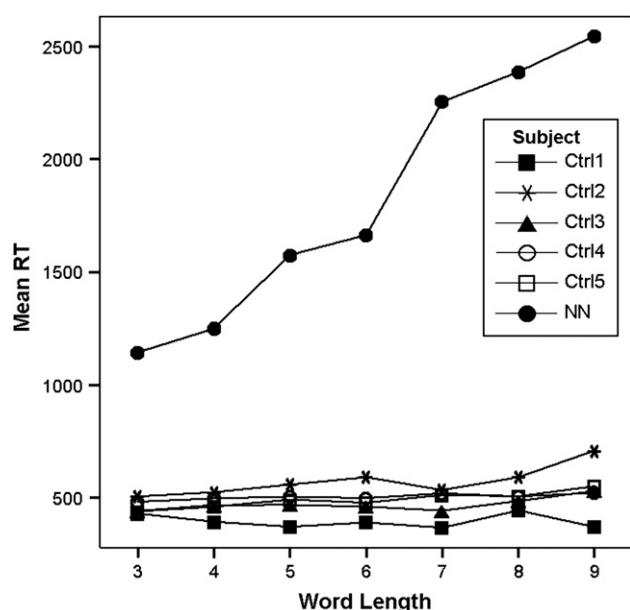


Fig. 2 – Plot of mean RTs for words of 3–9 letters from the PALPA subtest 31 for NN and five matched controls. NN’s mean RT was 1717 msec, compared to the control mean of 482 msec ($SD = 56$). The WLE for NN was 271 msec per letter.

We used two types of experiments in combination with the TVA modelling: single-stimulus report with central presentation (Experiment 1) and whole report with peripheral presentation (Experiment 2), both with two types of stimuli: letters and digits. In single-stimulus report experiments, the visual processing speed C and the perceptual threshold t_0 can be measured. At each trial a single stimulus (e.g., a letter) is briefly presented, followed by a pattern mask. This is repeated for many trials at varying exposure durations. Subjects are instructed to report the identity of the stimulus, and the responses are unsped. The test results are therefore based on accuracy of performance rather than RT, which implies that naming latency does not affect the test scores. The exposure duration is plotted against the mean identification score (see Fig. 4 for an example) and a maximum likelihood curve is fitted to the observed data. The curve can be used to calculate the two TVA parameters t_0 and C . The perceptual threshold t_0 is an extrapolated value of where the curve crosses the x-axis (i.e., mean score = 0). It represents the minimum exposure time needed for the subject to report any items, which is typically 10–20 msec in healthy subjects. The visual processing speed C can be calculated as the slope of the curve at $x = t_0$. C represents the efficiency of visual recognition: it describes the rate at which, as exposure time increases, the subject is better able to identify the stimulus.

Whole report tasks, where subjects have to report elements from a display of multiple unrelated stimuli, allow for the estimation of K – the visual apprehension span – as well as C . K represents the maximum ability to perceive multiple items in one view. It is calculated from the estimated upper limit (asymptote) of the subject’s mean score (see Fig. 5 for an example). To prevent eye movements, usually only exposure

durations below 200 msec are used in whole report. If the stimulus display is not followed by a mask, the effective exposure duration is prolonged for several hundred msec due to the visual afterimage, which is useful for testing subjects with relatively slow encoding rates. The prolongation of the effective exposure time can be modelled by TVA analysis (parameter μ). Note that in Fig. 5, exposure durations up to 500 msec are shown. These represent an unmasked exposure duration of 200 msec + μ .

4.2.2. Stimuli and procedure

In order to make the stimulus sets as similar as possible, we chose to use only ten letters, as there are only ten digits. To make the letters as easy to remember as possible, the first ten letters of the alphabet were chosen. The stimuli in Experiments 1 and 2 were computer generated, and did not conform to any known typefont. A very efficient pattern mask was generated by superimposing all letters and digits, as well as two mirror images (one “flipped” across the horizontal axis, one across the vertical) on each other. The stimulus sets and the mask are presented in Fig. 3.

In both experiments, a printed version of the relevant stimulus set (letters or digits) was placed in front of the subjects, and before each session they were encouraged to read through the printed stimuli. Importantly, NN had no difficulties reading the stimuli aloud. The stimuli were shown on a 19” monitor capable of 150 refreshes/sec (6.7 msec resolution). Participants were instructed to report the identity of the letters or digits only if “fairly certain”. Reports were unsped. Subjects were seated about 80 cm from the screen. To ensure central fixation before each trial, participants were instructed to focus on a centrally placed cross and indicate when they were ready. Eye movements were monitored by camera, and controlled by the experimenter online.

4.2.2.1. EXPERIMENT 1. SINGLE-STIMULUS REPORT: LETTERS VERSUS DIGITS.

4.2.2.1.1. METHOD. Experiment 1 was designed to measure NN’s visual processing speed, C , for single letters or digits in the centre of the visual field. Testing of letters and digits was performed in separate blocks of 120 trials. During the first test session, NN performed one block with digits and one with letters (in that order). A week later, he performed two sessions, each containing one block of each stimulus type, in an ABBA (letters first) design.² The controls received the blocks in the same order (BAABBA), two blocks per session. In each trial of the experiment a single white letter or digit was chosen randomly from the set of 10 stimuli (see Fig. 3) and flashed on a black background at the centre of fixation. The stimulus was immediately followed by a white pattern mask, which stayed on for 500 msec.

To obtain highly reliable estimates of each TVA parameter, 360 repetitions were performed for both the letter and digit version of the experiment (10 additional practice trials were run at the start of each session). The exposure duration in

² By accident, NN was presented with a block of letters using the original exposure durations during the second test session. These data have not been entered into the analysis. This extra block may have given NN more practice with letters than digits.



Fig. 3 – The computer generated letters and digits used as stimuli in Experiments 1 and 2, and the pattern mask employed in the same experiments.

a given trial was chosen randomly from a fixed set of values designed to characterize the full performance span from floor to ceiling scores. In the first test session (240 trials) there were five exposure durations: 13 msec, 20 msec, 27 msec, 40 msec, 53 msec. This set of values turned out not to be optimal, as NN's performance was close to zero at 13 msec and 20 msec and did not reach ceiling at 53 msec. As a consequence the exposure durations were changed in the second test session (480 trials) to the following four values: 27 msec, 40 msec, 53 msec, 80 msec. The control participants were tested using the exact same procedure and set of exposure durations.

The best-fitting TVA parameter values to the complete set of observed data for each participant were estimated by a maximum likelihood algorithm. The model fitting procedure was basically the same as in previous TVA-based patient studies (see Duncan et al., 1999; Kyllingsbaek, 2006, for mathematical details), but improved by a new fitting algorithm that corrects the TVA estimates for the influence of guessing. Using this modelling procedure the C parameter and the perception threshold t_0 were estimated separately for letters and digits. The model fits were close: on average the predictions correlated 98.4% with the observed data (98.6% in case of NN). For NN, the reliability of each C estimate was evaluated by 1000 bootstrap repetitions (see Habekost and Bundesen, 2003). The SD of such a large set of bootstrap estimates represents the standard (measurement) error (SE) related to the original parameter estimate. This value can be used to compute confidence intervals (CIs) of the parameter estimate (e.g., with 95% confidence the real value lies within ± 1.96 SE of the original estimate; Habekost and Rostrup, 2006).

4.2.2.1.2. RESULTS. In the 360 trials of single letter report NN scored 45% correct. The control group mean was 86.5% correct (SD = 4.6%), and NN's score deviation was highly significant ($p = .001$). NN's abnormal performance was reflected specifically in the TVA estimate of his visual processing speed: $C_{\text{letter}} = 22$ letters/sec (95% CI: [16.6; 26.7]). This was significantly reduced compared to the control group mean visual processing speed of $C_{\text{letter}} = 143$ letters/sec (SD = 47) ($p = .04$). Indeed, NN's visual processing speed was six times lower than the average normal level. NN's visual threshold was estimated at $t_0 = 13$ msec, not different from the control group the mean $t_0 = 13$ msec (SD = 2.4 msec).

For single digits NN's raw score was 55.3% correct. Compared to the control mean of 88.3% (SD = 2.6%), this was a highly significant reduction ($p < .001$). Concerning the more functionally specific TVA estimates, NN's visual processing speed was $C_{\text{digit}} = 42$ digits/sec (95% CI: [32.2; 51.1]). The average visual processing speed in the control group was $C_{\text{digit}} = 138$ digits/sec

(SD = 48). By Crawford and Garthwaite's test, NN's low C_{digit} value failed to reach significance ($p = .07$). This negative result was mainly due to the variability in the control group induced by a very high scoring individual, who had a C value of 223 digits/sec (the C values of the four other controls were in the range of 110–125). Because Crawford and Garthwaite's test assumes a symmetric distribution around the mean, the single high score implied that comparably low scores (e.g., NN's C value of 42) were evaluated as being within the normal range. Still, it is noteworthy that NN's C value was more than three times lower than the control mean and that all five controls had values that were between 2.6 and 5.3 times larger.

NN's perception threshold for digits was $t_0 = 18$ msec, while the control group mean threshold was $t_0 = 12$ msec (SD = 1.1 msec). Though not strongly elevated, NN's t_0 estimate was significantly different from the control group ($p = .003$) due to the very small normal variability of this parameter. See Fig. 4 for a graphical comparison of NN's letter and digit performance to a typical control participant.

Turning to the relative strength of letter and digit perception in each participant, NN's ratio between the C values for letters and digits was .52 (95% CI: [.35; .69]). Thus, digits were perceived about twice as fast as letters. For control participants, the average value was 1.05 (SD = .17), indicating nearly equal visual processing speed for the two stimulus types. NN's ratio was significantly different from the controls ($p = .02$), reflecting an abnormal difference between his ability to perceive letters and digits at fixation.

4.2.2.2. EXPERIMENT 2. WHOLE REPORT OF FIVE ITEMS: LETTERS VERSUS DIGITS.

4.2.2.2.1. METHOD. Experiment 2 was designed to measure NN's ability to perceive multiple independent stimuli at the same time. This corresponds to the TVA parameter K, the visual apprehension span. The K parameter is best estimated by whole report experiments in which multiple unrelated stimuli are shown for variable exposure durations (which also allows for estimation of the visual processing speed, C). In order to display many items at equal eccentricity, the stimuli were placed at the circumference of an imaginary circle. Because of NN's visual field cut, presentations were limited to the left side (central fixation was controlled in the same way as in Experiment 1, and monitored by video camera online). The stimuli were placed so peripherally that crowding effects between items were minimized, while letter recognition was still possible – about five visual degrees from fixation (viewing distance was not precisely controlled). In alternating test blocks either five letters or five digits were chosen from the stimulus sets used in Experiment 1. The stimuli were flashed on five equidistant locations on the half-circle for 30–200 msec followed by either a blank screen (so that the effective exposure duration was prolonged by a visual afterimage) or by five bright pattern masks shown for 500 msec (see Fig. 3 for stimuli and mask). Stimulus selection was random without replacement, so that the same letter/digit would never appear twice in the same display. The instruction was to report (unsped) the items one was “fairly certain” of having seen. For each of the five exposure durations (30 msec, 80 msec, 200 msec, 30 msec + afterimage, 200 msec + afterimage; randomly intermixed) 45 repetitions were performed (i.e., 225 trials for each of the two stimulus sets).

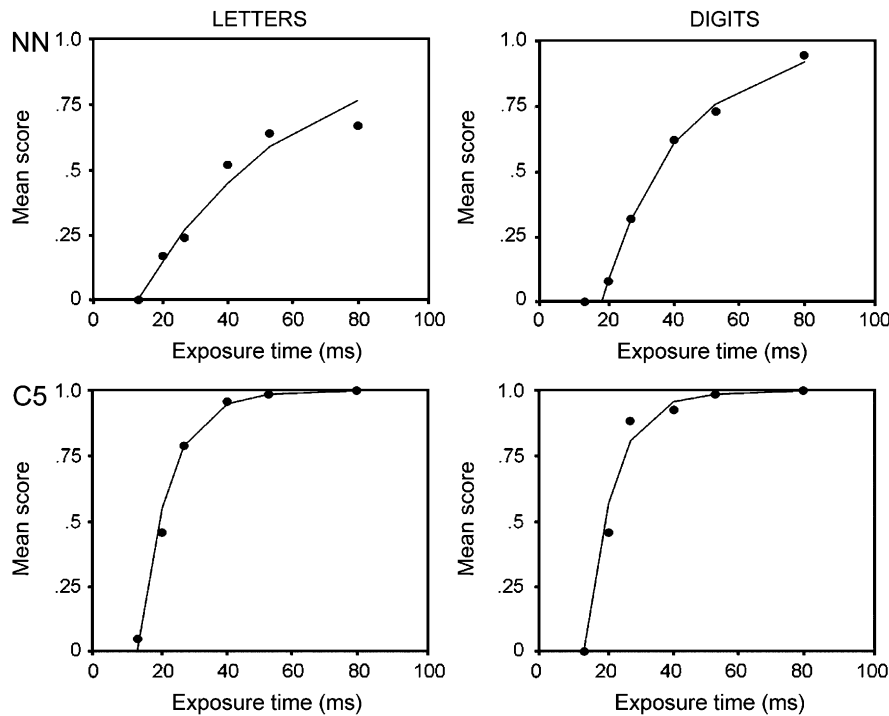


Fig. 4 – Performance in single-stimulus report by patient NN compared to a typical control participant (C5). Each panel shows the mean number of correctly reported letters/digits as a function of exposure duration. Solid curves represent maximum likelihood fits to the observations based on TVA analysis. The intercept with the x-axis corresponds to the perceptual threshold, t_0 . The slope of the curve at the intercept with the x-axis equals the visual processing speed for the stimulus, C .

For data analysis, the same TVA model fitting software as in Experiment 1 was used. For each stimulus type two main parameters were estimated: visual apprehension span, K , and visual processing speed, C (defined as the sum of the processing speeds at each of the five stimulus locations). The K parameter was estimated by non-integer values to improve the data fits. For example, a K value of 2.8 represents a probability mixture of visual short-term memory capacity at two and three items, occurring with 20% and 80% probability, respectively. The model fits on average correlated 93.6% with the observed data (98.4% in case of NN). 1000 bootstrap repetitions were carried out to assess the reliability of NN's estimates.

4.2.2.2. RESULTS. For letters, NN's visual apprehension span was 2.8 elements (95% CI: [2.50; 3.09]). This was significantly lower ($p = .008$) than the control group mean of 4.5 elements ($SD = .4$). Whereas control participants were often able to report all five stimuli at long exposures, NN could only report three letters at maximum. NN's visual processing speed in the tested part of the visual field was $C_{\text{letter}} = 22$ letters/sec (95% CI: [16.6; 27.2]). This was not significantly different from the control group mean of $C_{\text{letter}} = 28$ letters/sec ($SD = 8.5$).

For digits, NN's visual apprehension span was 2.7 elements (95% CI: [2.47; 2.85]), significantly lower ($p = .001$) than the control group mean of 4.5 elements ($SD = .3$). Thus the pattern was very similar to the K measurement for letters; the slight differences in estimated values can be accounted for by measurement error. NN's visual processing speed for peripherally presented digits was $C_{\text{digit}} = 32$ digits/sec (95% CI: [20.2;

44.7]). Again, this was not significantly different from the control group mean of $C_{\text{digit}} = 37$ digits/sec ($SD = 11$). See Fig. 5 for a graphical comparison of NN's letter and digit whole report performance to a typical control participant.

Comparing the results from Experiments 1 and 2, the control participants had about four times higher visual processing speed in the central than the peripheral visual field (mean ratio of peripheral vs central C for letters: .20, $SD = .067$; for digits: .28, $SD = .076$). By contrast, NN had roughly equal central and peripheral C values for both letters and digits (C ratios: 1.01 and .78, respectively; both values differed significantly from the control means: $p < .001$ and $p = .002$, respectively).

Overall, Experiment 2 showed an interesting mixture of impaired and preserved visual function in NN. On the one hand, NN's capacity to simultaneously perceive multiple unrelated items was markedly reduced. On the other hand, sensory processing in the peripheral visual field was surprisingly normal compared to perception of centrally located stimuli: visual processing speed was within the normal range and the abnormal difference between letter and digit perception found in Experiment 1 was also absent.

4.3. Capacity limitations and letters in words

In order to test whether NN's reductions in visual capacity also affected his reading of words, we presented him with a task probing the word superiority effect (WSE). In normals, the ability to report letters embedded in words is usually superior to letter report from random letter strings (e.g., Bowers et al.,

1996; McClelland and Johnston, 1977). This effect has been reported in some patients with pure alexia (e.g., Reuter-Lorenz and Brunn, 1990), while in other pure alexic patients the effect is absent (e.g., Behrmann et al., 1990; Kay and Hanley, 1991). As reading centrally presented words could potentially be affected by NN's quadrantanopia, we presented half the words (and nonwords) below fixation to see if NN's performance would be different in this region of the visual field.³

4.3.1. Experiment 3. Word superiority

4.3.1.1. STIMULI AND PROCEDURE. We designed a stimulus set of 115 five-letter words and 115 nonwords. The nonwords were created by jumbling the letters of the 115 words. We ensured that none of the nonwords contained words or word fragments, but their pronounceability varied.⁴ Half the real words were high frequent (>20 per million), half were low frequent (<10 per million, Bergenholtz, 1992).

The procedure was similar to Experiment 2. The participants were required to focus on a centrally placed cross and indicate when they were ready. The experimenter then pressed a key, and a word/letter string was presented either at fixation or about 1.8 visual degrees below fixation. Stimuli were presented for 100 msec in 36 point Times New Roman (white on black background), followed by a pattern mask (five repetitions of the mask used in Experiments 1 and 2). Subjects were asked to report as many letters as possible from the display, but refrain from naming words. This has been shown to yield the most reliable measures of WSE (Bowers et al., 1996; McClelland and Johnston, 1977). Subjects were asked to name the letters from left to right. They were told that both words and nonwords would be presented.

The results were calculated on the basis of number of correct letters reported. Number of correct whole words/letter strings can also be calculated, but NN never reported all five letters correctly, and the analysis was therefore restricted to correctly reported letters.

4.3.1.2. RESULTS. NN reported significantly fewer letters correctly from words (mean correct letters 2.09) than controls [mean (SD) correct letters 4.78 (.19), $p < .001$]. The same was true for nonwords, where NN reported a mean of 1.66 letters, and the controls 3.88 (SD = .42, $p < .01$). NN's low scores in this test are not mainly due to errors, but omissions: on average he reported 2.5 letters from words and 2.16 from nonwords. An independent sample t-test of NN's scores for words versus nonwords revealed that he reported significantly more correct letters from words than nonwords ($p < .001$). The controls also reported more correct letters from words than nonwords, and this difference was significant for each individual control. There was no

significant effect of lexical frequency on letter report for NN, while one control showed a significant effect of frequency. NN reported more correct letters from centrally presented strings than those presented below fixation (mean correct central: 2.25; below fixation: 1.50, $p < .001$), a pattern also found in the controls.

To check for effects of pronounceability, we broke the analysis down in pronounceable and non-pronounceable nonwords, choosing a pronounceability cut-off of <.5 for non-pronounceable ($N = 57$), and <1.5 for pronounceable nonwords ($N = 33$).⁴ Unless otherwise stated, this analysis is performed collapsed over presentation mode (see Table 3 for results in the individual conditions). There was no significant difference between NN's performance with words (mean correct 2.09) and pronounceable nonwords (mean correct 1.88, $p = .224$), but he reported significantly more letters from words than from unpronounceable nonwords (mean correct 1.54, $p < .001$). In contrast, the controls reported significantly more letters from words (mean correct 4.78) compared to pronounceable nonwords (mean correct 4.08, $t_4 = 4.9$, $p = .008$), but showed no significant difference between letter report from pronounceable versus non-pronounceable nonwords ($t_4 = 2.6$, $p = .108$).

For centrally presented letter strings, NN's performance with words (mean correct 2.47) and pronounceable nonwords (mean correct 2.5, $p = .879$) was strikingly similar, while his performance with non-pronounceable nonwords (mean 1.74 letters) was inferior to both these conditions ($p < .01$). For words presented below fixation, there were no significant differences between the three conditions. This indicates that NN's performance is affected more by pronounceability than lexicality. This could reflect a higher order influence on letter recognition, or simply that it is easier to remember pronounceable strings of letters. The fact that NN never reported a whole word may indicate that the latter explanation is to be favoured. Regardless of whether the superiority in NN's performance reflects "wordness" or pronounceability, there is one very striking aspect of his performance; he rarely reported more than three letters correctly (four letters were correctly reported in 2/230 trials). Even if NN profits to a degree from the stimulus being a word – or being pronounceable – instead of a random, non-pronounceable letter string, he can still not overcome his capacity limitations and encode more than 2–3 items into his visual short-term memory. The fixed single exposure duration does not allow us to decide whether it is NN's processing speed or his visual apprehension span that limits his letter reporting ability in this experiment. What seems clear though, is that for NN, "letters in familiar words suffer some of the same processing competition as unrelated processing displays." (Duncan et al., 2003, p. 699).

4.4. Object processing

While NN performed normally in a naming task with line drawings (see Section 4.1.4), he might be impaired in tasks demanding more fine grained perceptual differentiation than is required in basic level naming. To examine this, we presented NN with an object decision task with line drawings. We also presented him with an object decision task with fragmented drawings of the same material, as this task may induce the "impoverished perceptual conditions" suggested by Sekuler and Behrmann (1996) to affect visual recognition in pure alexic

³ We also conducted a reading test in this part of the visual field, with words of 3–7 letters. This generally reproduced the results in the initial reading test. NN's mean RT was 1993 msec in this part of the visual field, and his WLE was 345 msec per letter.

⁴ Nonword pronounceability was rated by eight independent subjects, including the authors, according to the following scoring system: 2 = pronounceable, 1 = perhaps pronounceable, I am unsure, 0 = not pronounceable. The mean of these ratings yielded the pronounceability score which varied continuously from zero (not pronounceable) to two (pronounceable).

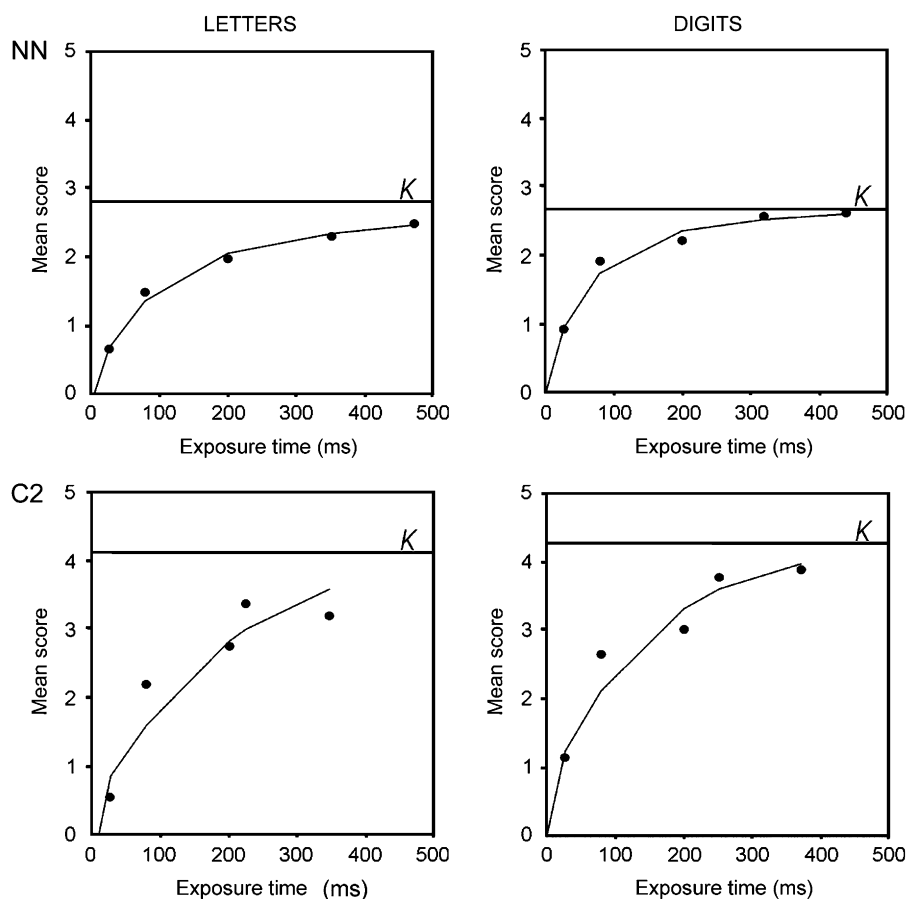


Fig. 5 – Performance in whole report by patient NN compared to a typical control participant (C2). Each panel shows the mean number of correctly reported letters/digits as a function of exposure duration. Solid curves represent maximum likelihood fits to the observations based on TVA analysis. The intercept with the x-axis corresponds to the perceptual threshold, t_0 . The slope of the curve at the intercept with the x-axis equals the sum of the visual processing rates for the five stimuli, C . The asymptotic level of performance corresponding to the maximum capacity of visual short-term memory, K , is marked by a horizontal line.

patients. NN received these two tasks on separate occasions with a four week interval. He was presented with the full line drawing task first. The controls first performed the task with fragmented drawings, in order to minimize the carry-over effect. All controls performed the two tasks in different sessions. This order of presentation should give the controls an advantage in the (easier) task with line drawings, while giving NN an advantage in the more difficult task with fragmented drawings.

4.4.1. Experiment 4. Object decision with line drawings

4.4.1.1. STIMULI AND PROCEDURE. 80 black and white line drawings taken from the set of Snodgrass and Vanderwart (1980), and 80 nonobjects mainly taken from the set of Lloyd-Jones and Humphreys (1997), were presented centrally on a computer screen. Subjects were asked to decide if the picture represented a real object or a nonsense object. Because the nonobjects are chimeric line drawings of closed figures, constructed by exchanging single parts belonging to objects from the same category, they resemble real objects to a great extent which makes the discrimination between real objects and nonobjects quite demanding. The pictures subtended $3\text{--}5^\circ$ of visual angle

and were presented until a response was made on a serial response-box (middle finger for real object, index finger for nonobject). Subjects responded with the left hand, and were instructed to respond as fast and as accurate as possible. A practice version of the test with 16 stimuli was performed before the actual task. The pictures from this practice version were not included in the actual test. Overall error rate, as well as RTs to correctly categorized real objects and nonobjects were analysed.

4.4.1.2. RESULTS. NN made 7 errors in this task, while the controls made 7.4 errors on average ($SD = 3.56$). NN's mean RT was 922 msec ($SD = 369$) for real objects, not significantly different from the control group mean of 1038 msec ($SD = 262$, $p = .353$). For nonobjects, NN's mean RT was 998 msec ($SD = 472$), while the control group mean RT was 1114 msec ($SD = 231$, $p = .335$). Thus NN's performance was within the normal range on this test.

4.4.2. Experiment 5. Object decision with fragmented pictures

4.4.2.1. STIMULI AND PROCEDURE. The stimuli, experimental setup and instructions were the same as in the object decision task described above (Experiment 4), except that all the pictures

Table 3 – Mean letter report by pronounceability for all stimuli, and divided by presentation mode (central and below fixation) for NN and the control group in Experiment 3.

	NN mean (SD)	Control mean (SD)
<i>All trials</i>		
Words	2.09 (.85)	4.78 (.19)
Pronounceable nonwords	1.88 (.89)	4.08 (.45)
Non-pronounceable nonwords	1.54 (.80)	3.88 (.42)
<i>Central presentation</i>		
Words	2.47 (.60)	4.89 (.07)
Pronounceable nonwords	2.50 (.69)	4.54 (.32)
Non-pronounceable nonwords	1.74 (.76)	4.32 (.33)
<i>Below fixation</i>		
Words	1.71 (.89)	4.67 (.35)
Pronounceable nonwords	1.29 (.69)	3.66 (.68)
Non-pronounceable nonwords	1.37 (.81)	3.48 (.53)

were fragmented. The fragmented forms were made by imposing a mask as a semi-transparent layer on the full line drawings. This mask consisted of blobs of different size and shape. The line drawing and the mask were subsequently merged into a single layer yielding a fragmented version of the line drawing (see Fig. 6). The same mask was used for the generation of all fragmented stimuli. Overall error rate, as well as RTs to correctly categorized real objects and nonobjects were analysed.

4.4.2.2. RESULTS. NN made 46/160 errors whereas the control subjects on average made 43.2 (SD = 4.66). NN's mean RT was 1466 msec (SD = 717) for real objects, significantly slower than the control group mean of 995 msec (SD = 60, $p = .001$). NN's mean RT for nonobjects was 1475 msec (SD = 654), not significantly different from the control group mean of 1701 msec (SD = 301, $p = .265$). Normally, subjects are faster at categorizing real objects than nonobjects (Gerlach, 2001), a pattern also found in the controls in this experiment ($t_4 = 5.92$, $p < .004$). NN, on the other hand, did not exhibit the normal "real object superiority effect" with fragmented drawings ($t_{112} = .07$, $p = .948$).

5. Discussion

We have described a patient (NN), who suffers from pure alexia after a haemorrhage in the posterior part of the left cerebral hemisphere. NN has no agraphia or other aphasic symptoms. His lesion includes striate cortex, the middle occipital gyrus, as well as the inferior part of the lingual gyrus and the posterior and mid portion of the fusiform gyrus. NN shows a WLE in single word reading of about 270 msec per letter, and his average time to read single words is elevated compared to a group of matched controls. NN has an upper right quadrantanopia.

Experiment 1 revealed that NN's recognition of singly presented letters is impaired; his processing speed for

centrally presented single letters is severely reduced compared to controls. His recognition of centrally presented single digits is also impaired, although better than his recognition of letters. A whole report task (Experiment 2) revealed that NN has a reduced visual apprehension span for both letters and digits. He is only able to encode maximum three symbols into his visual short-term memory, which is markedly reduced compared to the control subjects who were able to encode up to five elements simultaneously. As NN's auditory span is at least five items, a generally reduced span cannot account for this deficit. NN's processing speed was not reduced in the whole report experiment – where stimuli were presented in the peripheral part of the left visual field – for either letters or digits. NN is no better at reporting letters from words or pronounceable nonwords (Experiment 3) than from the whole report displays of five independent letters. Even with stimuli that ought to be familiar (words) presented in a familiar typefont in the centre of the visual field, he seems unable to exceed the capacity limitations evident for unrelated stimuli. His performance with line drawings is normal both in a timed naming task and in an object decision task (Experiment 4). However, in an object decision task with fragmented objects (Experiment 5), NN's RTs to the real objects are elevated compared to controls.

How can we relate these findings to the theories of pure alexia presented in the Introduction? An alphabetical account of pure alexia seems insufficient to explain his performance. Damage to a system dedicated to "extracting abstract letter identities" (Cohen et al., 2004), or "parsing letter strings into ordered familiar units" (Warrington and Shallice, 1980) should not affect processing of digits. Thus it seems we must look for the cause of his deficit at a different level.

According to the simultanagnosia hypothesis of pure alexia (e.g., Farah, 1990), the reading deficit arises due to a fundamental problem in perceiving multiple items in parallel. In the strictest sense, this implies that NN's span of apprehension should equal one, which is clearly not the case. In fact, NN's performance does not seem to be primarily related to the number of items presented. He shows clear impairments both for single letters presented centrally (Experiment 1), for unrelated letters presented peripherally (Experiment 2), and for words and strings of unrelated letters presented centrally (Experiment 3). A simultanagnosic deficit – where recognition of single items should be intact, and/or perception of multiple items disproportionately impaired – does not seem like the appropriate explanation for NN's alexia. Although NN's reduced apprehension span may contribute to his reading deficit, it cannot explain his performance with single stimuli.

The final main hypothesis of pure alexia suggests that it is due to a general visual deficit that affects visual input regardless of stimulus category (e.g., Behrmann et al., 1998a). This can possibly account for NN's impairment with both letters and digits in single and multiple displays. In particular, NN's reduced recognition efficiency for centrally presented letters and digits seems to indicate a general disturbance. It is peculiar, and was unexpected, that while the central, or foveal, processing speed of our controls far supersede their speed in the periphery of the visual field, NN's speed of processing for letters is similar in the two regions. Thus, some



Fig. 6 – Examples of fragmented object (left) and nonobject used as stimuli in Experiment 5.

kind of “acuity” or “foveal superiority” seems to be missing in NN, and this pattern could point to a form of “foveal amblyopia”, where shape perception is disproportionately impaired in the centre of the visual field. This reduced central processing speed is not selective to letters, but affects digits also, suggesting that a general rather than letter specific process is affected. We suggest that NN’s reduced central processing speed reflects a deficit in building stable sensory representations of shapes. As shape perception in the central visual field is extremely important in reading (Rayner and Bertera, 1979), this deficit is likely to contribute significantly to NN’s alexia.

NN’s reduced visual apprehension span may be accounted for by the same basic deficit: if his sensory representations are crude or unstable, it will be harder to maintain multiple representations in visual short-term memory without interference. The result could be impaired ability to encode multiple letters from brief displays, influencing both perception of unrelated letters (Experiment 2) as well as words (Experiment 3). It should however be noted that the setup of Experiment 3 does not allow us to decide whether reduced processing speed, reduced apprehension span, or both, are responsible for NN’s impaired word perception.

As argued above, a low level deficit affecting sensory representations of visual stimuli can account for NN’s reading pattern and his performance in Experiments 1–3. Nevertheless, NN performed normally in a computerized object naming task, and in the more perceptually demanding object decision task (Experiment 4), observations which may be harder to reconcile with a general visual deficit. To our knowledge, normal performance with regards to both errors and RTs in such tasks has not previously been reported in pure alexia, and this provides evidence that recognition of line drawings can be intact in this disorder. However, in a more difficult version of the object decision task, using fragmented versions of the line drawings (Experiment 5), NN’s performance is different from that of controls as he responds significantly slower to real objects. We suggest that this reflects a combination of the impoverished nature of the stimulus material and NN’s unstable sensory representations (as suggested above). NN’s normal performance with line drawings (Experiment 4), can probably be explained by the cues to perceptual organization, e.g., closure and continuity, that the regular drawings provide: the redundancy of information provided by regular line drawings compared with fragmented line drawings may be sufficient to support efficient object recognition even when basic sensory representations are degraded. This explanation resembles the suggestion by Sekuler and

Behrmann (1996), that pure alexia is caused by a perceptual deficit common to word and object processing which “is unmasked in situations where few intrinsic perceptual cues exist to aid in the integration of multiple parts of an object, such as in reading” (p. 972).

It has been suggested (e.g., Starrfelt and Gerlach, 2007) that visual object recognition entails a stage of shape configuration, and that processing on this stage can be augmented in a top-down manner via access to stored object knowledge (Gerlach et al., 2002, 2006). This yields familiar objects an advantage during visual processing because only familiar objects (as opposed to nonobjects in the present case) are associated with stored object representations which can aid the configuration process. This top-down process seems to work efficiently for NN with regular line drawings. Control subjects can also derive sufficient information from the fragmented drawings to support a first pass access to stored object knowledge, which in turn can augment the configuration process. However, when objects are fragmented, NN no longer benefits from object familiarity. Due to his degraded sensory representations of the stimuli, NN is unable to extract sufficient information from the fragmented drawings to support this top-down processing. This explains why NN is impaired with fragmented objects, but not with fragmented nonobjects where top-down processing does not influence performance. It is an intriguing thought that NN may fail to show normal effects of familiarity in both reading (visual capacity affects his letter report from words), and recognition of fragmented objects (lack of real object superiority effect) for the same reason, and it would be interesting to investigate this more directly in future studies.

In sum, NN’s performance with outline drawings is normal even with regards to RTs, which to our knowledge has never been shown in a patient with pure alexia. Still, we have demonstrated that NN has deficits in visual processing of both letters, digits, and complex pictorial stimuli. Neither a disturbance to a system specialized for letter or word perception nor a deficit in simultaneous perception can explain this pattern of performance. Of the main theories of pure alexia, only the hypothesis of a “general visual deficit” can explain our findings. This general hypothesis is not very specific regarding which process(es) are impaired. We have suggested that an impairment in the build-up of sensory representations of visual stimuli can account for NN’s performance in our experiments. A recent account of pure alexia (or LBL reading) suggests that the responsible low level deficit could be related to the spatial frequencies of stimuli; specifically that patients

with pure alexia are impaired in extracting “the optimal spatial frequency band for letter and word recognition” (Fiset et al., 2006, p. 1466). Such a deficit could potentially explain all the deficits we have shown in NN: it would degrade the sensory representations of both letters and digits, and thus affect perception of these symbols in both single and multiple displays. When central visual processing speed for letters is very low, one needs to fixate longer at each segment of text to derive the same information as a normal reader. Further, if the visual span is reduced, less of the surrounding text can be apprehended, which prohibits the normal pattern of relatively large amplitude saccades between content words. In combination, severe deficits in visual speed and span should therefore result in a very slow and laborious reading process with longer fixations and shorter saccades, precisely what is found in patients with pure alexia (Behrmann et al., 2001). Concerning object perception, Fiset et al. (2006) claim that perception of most everyday objects would not be affected by this insensitivity to medium range spatial frequencies, with the exception of “complex natural objects”. Our fragmented stimuli may be seen as representing a class of complex objects, in which case all our findings can be explained by one single low level deficit.

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