How low can you go?

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Short Communication

How low can you go: Spatial frequency sensitivity in a patient with pure alexia ☆

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ABSTRACT

Pure alexia is a selective deficit in reading, following lesions to the posterior left hemisphere. Writing and other language functions remain intact in these patients. Whether pure alexia is caused by a primary problem in visual perception is highly debated. A recent hypothesis suggests that a low level deficit – reduced sensitivity to particular spatial frequencies – is the underlying cause. We tested this hypothesis in a pure alexic patient (LK), using a sensitive psychophysical paradigm to examine her performance with simple patterns of different spatial frequency. We find that both in a detection and a classification task, LK's contrast sensitivity is comparable to normal controls for all spatial frequencies. Thus, reduced spatial frequency sensitivity does not constitute a general explanation for pure alexia, suggesting that the core deficit in this disorder is at a higher level in the visual processing stream.

1. Introduction

Pure alexia is an acquired reading disorder that affects reading but not other language functions. Even writing is preserved, while reading is slow but mostly correct. A notable feature of pure alexia is the word length effect (WLE): Reaction times in reading increase linearly with word length for these patients, while in normal readers word length has little impact on reading times when words are shorter than five or six letters (Weekes, 1997; but see Cumming, Patterson, Verfaille, & Graham, 2006). The WLE is often interpreted as reflecting letter-by-letter (LBL) reading; the patients are thought to process letters serially rather than in parallel (e.g., Cohen et al., 2004).

The cognitive deficit underlying pure alexia is highly debated. Some argue that the disorder, at least in its purest form, affects reading only (e.g., Cohen et al., 2004; Gaillard et al., 2006; Yong, Warren, Warrington, & Crutch, in press) while others have suggested that a more general visual deficit causes the observed reading problems (Farah & Wallace, 1991; Fiset, Gosselin, Blais, & Arguin, 2006; Starrfelt, Habekost, & Leff, 2009). In general, the suggested "general visual deficit" thought to cause pure alexia has been relatively underspecified (although see Farah, 2004, for an exception). However, in 2006, building on several studies of patients with pure alexia/LBL-reading as well as experimental studies of normal subjects, Fiset et al. suggested a straightforward and testable hypothesis, namely that the LBL-reading pattern is caused by a reduced sensitivity to particular spatial frequencies. This reduced sensitivity is thought to affect medium-to-high spatial frequencies (Fiset et al., 2006; Tadros, Fiset, Gosselin, & Arguin, 2009) that are of particular importance for word recognition (Tadros, Dupuis-Roy, Fiset, & Arguin, 2010).

Anatomically, pure alexia has been linked to lesions in the left fusiform gyrus affecting the so-called visual word form area (VWFA; Cohen et al., 2004; Dehaene & Cohen, 2011; Leff, Spitsyna, Plant, & Wise, 2006; Starrfelt et al., 2009). Interestingly, a recent fMRI study has shown stronger activation to sine-wave gratings of high compared to low spatial frequencies in the VWFA, while the opposite was true for the corresponding areas in the right hemisphere (Woodhead, Wise, Sereno, & Leech, 2011). This led Woodhead et al. (2011) to suggest that spatial frequency sensitivity may be a potential locus of the visual deficit in pure alexia. The aim of the current study was to put this hypothesis to a direct test by investigating contrast sensitivity for different spatial frequencies in a patient with pure alexia and LBL-reading. If lack of sensitivity to certain medium or high spatial frequencies is important in causing this reading deficit, the patient should show selective impairment in performance with stimuli with these particular spatial frequencies, while sensitivity to other frequencies should remain intact or relatively preserved.

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We report a study of patient LK, who shows the classical features of pure alexia: elevated reaction times (RTs) in single word reading, a significant word length effect, and preserved writing and language skills. The contrast sensitivity function (CSF) for LK and controls was determined in two different tasks. The spatial frequency hypothesis suggests that *sensitivity* for certain spatial frequencies should be affected in pure alexia, and thus testing our patients' ability to *detect* sinusoidal gratings of different frequencies at different contrast levels should be sufficient to test the hypothesis. However, as reading and letter identification demands not only detection of the important spatial frequencies, but also the ability to categorize or classify them, we decided to test LK's CSF in both a detection and a discrimination task. In the Detection task, participants had to detect the temporal interval in which a Gabor patch was presented, while in the Discrimination task, participants were asked to decide the orientation of a Gabor patch (horizontal or vertical).

2. Results

2.1. Participants

Patient LK was 29 years old at the time of this investigation (November 2011). She is right handed (Edinburgh handedness inventory laterality quotient + 100, Oldfield, 1971), and was studying for a Master's degree at the time of her injury (in 2008). At present, LK extensively uses computer software to compensate for her diminished reading skills. Following her partial recovery, she has finished her MA in philosophy, receiving the highest possible grade for her master's thesis! She has corresponded extensively with the authors using email, and her writing in this correspondence is flawless. She is now pursuing an academic career, in spite of her persistent reading problems.

An MRI performed at the time of this investigation revealed a lesion centred on the left occipito-temporal cortex (see Fig. 1). Posteriorly, the lesion affects lateral and inferior occipital cortex, with medial extension into the white matter at the depth of the calcarine sulcus. Moving anteriorly, the lesion affects the lateral part of the fusiform gyrus, the adjacent lateral occipitotemporal sulcus and the inferior temporal gyrus. The mid portion of the fusiform gyrus is spared, but the white matter above it (inferior longitudinal fasciculus including the inferior fronto-occipito fasciculus) is affected. The most anterior extent of the lesion is level with the most posterior part of the splenium of the corpus callosum. There is also evidence that an external ventricular drain was placed at some point through the right frontal lobe, with some focal damage of the genu of the corpus callosum.

LK's performance was compared to 10 control participants, matched for age (LK = 30; controls = 31.5 (SD = 2.5), educational degree (MA), final grade (LK = 12; controls = 10.9 (SD = 1.5), and handedness (right). All controls had normal or corrected to normal vision, and no history of neurological or psychiatric illness or dyslexia. LK 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).

2.2. Background testing

In 2009–2010, preliminary testing in our lab revealed that LK showed elevated reaction times in word reading, a significant word length effect, and slow and effortful text reading. She made very few reading errors. Her writing was flawless, as evidenced by writing sentences and single words (PALPA subtest 31). In 2010, LK's reaction times (RTs) in naming 40 Snodgrass and Vanderwart (1980) line drawings were significantly elevated (LK's mean RT was 1040 ms, mean (SD) of a group of 14 elderly controls are 770 (84), $t = 3.335$; $p = .003$, Crawford and Howell's test; see Starrfelt, Habekost, & Gerlach, 2010 for a description of this task). Her visual fields were tested with a computerized perimetry (Kasten, Gothe, Bunzenthal, & Sabel, 1999), where she responded to all stimuli in both visual fields, indicating that the hemianopia previously noted had remitted. In a test of visual attention for peripheral visual stimuli (Whole report, see Starrfelt et al., 2010 for details), LK's visual processing speed for letters was found to be impaired, particularly at two positions in the upper right quadrant, where

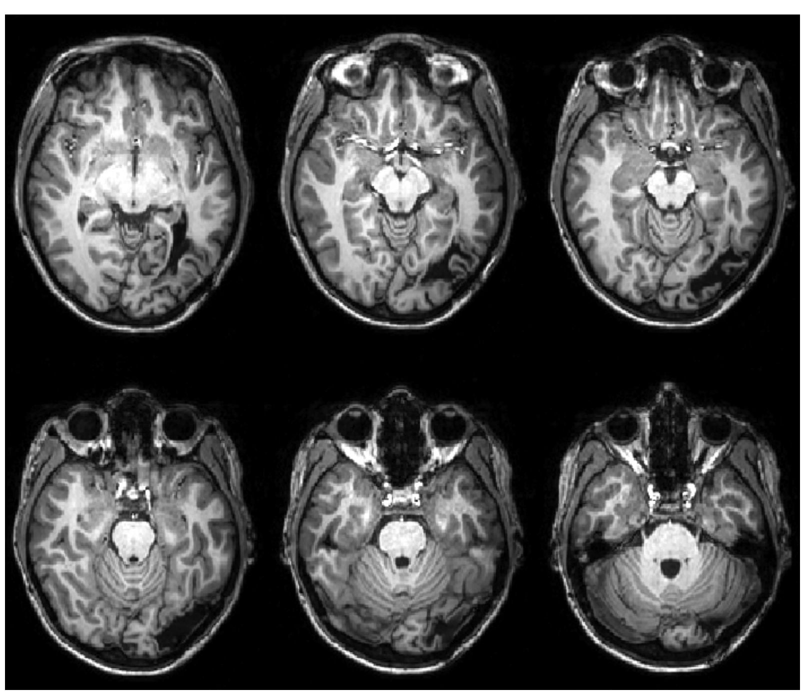

Fig. 1. MRI-scan of LK's lesion in the left occipito-temporal cortex (see text for anatomical description).

information uptake was close to zero. This could indicate impaired shape processing in this part of the visual field (cf. Habekost & Starrfelt, 2006). Her visual apprehension span was around three items, lower than the normal level of 4–5 items in this test, but similar to other patients with pure alexia (Starrfelt et al., 2009, 2010). The reduction in visual apprehension span affected both visual fields.

3. Experimental results

3.1. Single word reading

LK made two reading errors in the reading test, which consisted of 150 words of 5–7 letters. Another 11 trials had to be excluded due to voice key error. The controls made an average of 2 (range 0–9) voice key errors, but no reading errors. LK's overall mean RT was 2295 ms (SD = 821), significantly higher than the controls' mean RT of 471 ms (SD = 78; $t = 22.3$; $p < .001$, Crawford and Howell's test). LK showed a significant effect of word length on RTs of 242 ms per letter ($r^2 = .057$, $F(1, 134) = 8.121$, $p < .01$). The mean WLE for the controls was 9 ms (SD = 9), and this effect was significant in three participants (WLE's of 13 ms, 13 ms and 19 ms respectively, all $p < .05$).

3.2. Spatial frequency sensitivity

See Fig. 2 for an illustration of the experimental procedures. The results from the Detection and Discrimination tasks are illustrated in Fig. 3. The Contrast Sensitivity Function is calculated as the reciprocal contrast thresholds for each Gabor frequency, and displayed on a logarithmic scale.

We also compared LK's sensitivity-score for each spatial frequency, in both experiments, to the mean of the control group using Crawford and Howell's (1998) test. This analysis revealed no significant difference between the patient and the matched controls for any of the Gabor frequencies, in any task (all p's > .35, two-tailed).

4. Discussion

We find no evidence of reduced contrast sensitivity for any of the tested spatial frequencies in patient LK. Although she shows the classical features of pure alexia: elevated reaction times in single word reading, a significant word length effect, and preserved writing, her contrast sensitivity was comparable to normal controls across a wide range of spatial frequencies when tested in a demanding psychophysical test-paradigm. This strongly argues against the hypothesis that reduced sensitivity to particular medium-to-high range spatial frequencies can explain the deficient reading shown by patients with pure alexia. We have only tested one patient with this paradigm, and thus it remains possible that other patients with pure alexia or letter-by-letter reading do show reduced sensitivity for certain spatial frequencies. Indeed, a recent study has shown reduced sensitivity to higher spatial frequencies (tested on an optometric chart) as well as impaired processing of complex visual material in a group of alexic patients/LBL-readers (Roberts et al., in press). However, as LK's scores are well within the normal range on two very sensitive tests of spatial frequency sensitivity, it does not seem plausible that such a deficit necessarily accompanies pure alexia, and thus it does not constitute a general explanation for this disorder.

A "general visual deficit" has been suggested by many to be the core deficit in pure alexia (e.g., Behrmann, Nelson, & Sekuler, 1998; Farah, 2004; Roberts et al., in press; Starrfelt & Behrmann, 2011; Starrfelt et al., 2009, 2010.), and the spatial frequency hypothesis has by far been the most straightforward and testable in its conceptualisation of the exact visual process at stake. Fiset et al. (2006) and Tadros et al. (2009) used word stimuli where some spatial frequencies were filtered out in their studies of spatial frequency effects on normal and LBL-reading, and it is possible that our patient would show an abnormal pattern of performance had we used more complex stimuli in our investigation. We decided, however, to test her with the simplest possible stimuli, aiming to isolate the process of perceiving spatial frequencies in themselves, rather than words or letters. As the hypothesis suggests that the *sensitivity* to certain spatial frequencies should be reduced in pure alexia, this was the simplest and most direct test of the hypothesis.

Although we do not find evidence for a deficit in this particular low-level visual process, we are still inclined to interpret LK's alexia as being the result of a deficit affecting processing of visual stimuli in general, rather than a deficit specific to word or letter processing. This would explain why she is impaired not only in reading, but in picture naming, and also shows reduced visual processing speed and visual apprehension span. The current study does not allow us to infer much more about the nature of this

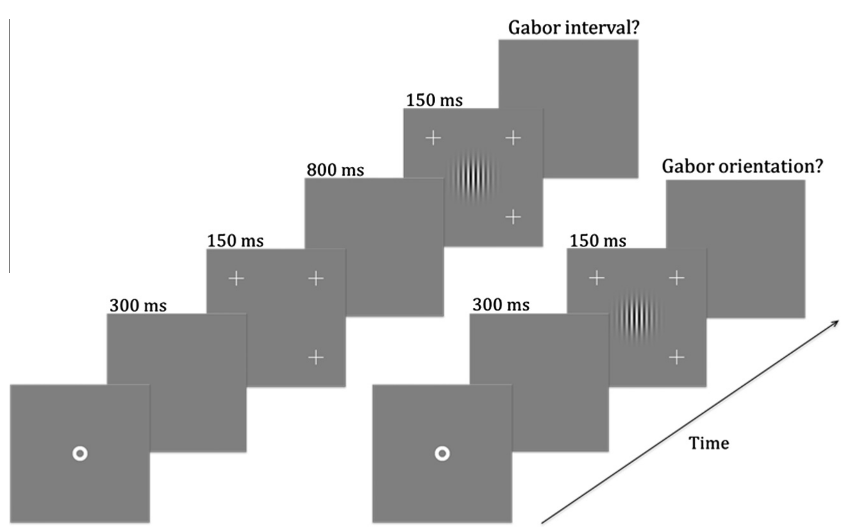

Fig. 2. Illustration of the experimental paradigms. Left: detection experiment where observers are required to detect which interval a Gabor patch appeared in. Right: discrimination experiment where observes are required to detect the orientation of a Gabor patch.

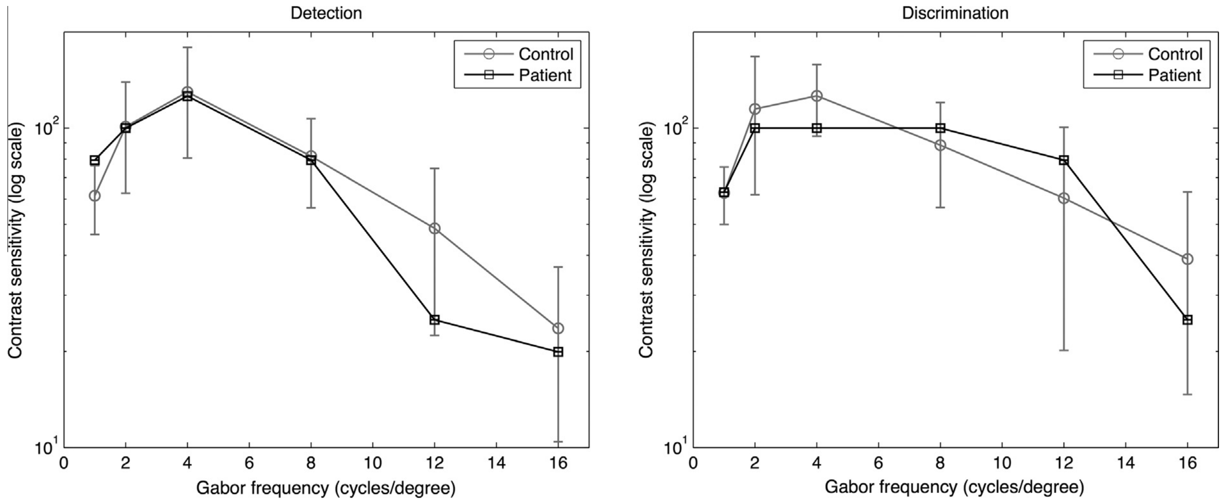

Fig. 3. Schematic representation of results from the detection experiment (left) and the discrimination experiment (right). CSF (reciprocal contrast threshold) is depicted as function of Gabor frequency on a log10 scale for patient LK and the control group. Error bars represent the standard error of the mean.

'general deficit' other than this: it is on a processing level higher than extraction of simple spatial frequency patterns.

5. Methods

5.1. Case report

In 2008, LK suffered an intra-cerebral hematoma caused by an arterio-venous malformation (AVM) in the territory of the posterior cerebral artery. The hematoma was evacuated, and the AVM treated surgically. Because of elevated intracranial pressure, a ventriculo-peritoneal shunt was placed on the right side. According to a neuropsychological assessment in the subacute phase, LK showed symptoms of alexia without agraphia, and slight affection of the right visual field (partial hemianopia). Mild word finding difficulties and slightly impaired working memory were also noted. Tests of figure copying, block design, and identification of fragmented pictures (Street completion test) were performed within normal limits, and verbal abstraction was noted to be good. LK experienced photophobia and extreme tiredness for a long period following her injury (+1 year). At the time of the present investigation she was receiving methylphenidate against her tiredness.

5.2. Experimental investigation

The present investigation was performed over three sessions during November 2011. The reported experiments were part of a larger investigation of LKs reading and visual perception. To statistically compare performance between the patient and the controls, we used Crawford and Howell's (1998) test. All reported *p*-values for this test are one-tailed unless otherwise specified.

5.2.1. Single word reading

5.2.1.1. Stimuli. 150 words of 5–7 letters were used to determine mean RTs and the effect of word length on reading.[1] The words were matched across word lengths for word frequency (all words were <10 per million; Bergenholtz, 1992) and N-size (metric kindly provided by the Society for Danish Language and Literature).[2]

5.2.1.2. Procedure. The test was run using E-prime 1, in a dimly lit room. Words were written in Courier New Font size 40, and were presented in capital letters in white on a black background on a CRT screen. Subjects were seated approximately 60 cm from the screen. RTs from word onset were measured with a voice key. Errors were recorded by the experimenter. 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. The interval between response and presentation of the next stimulus was 2 s. A practice version with ten words was administered before the actual test. Voice key errors (setting it off to early or too late) were removed before the analysis.

5.2.2. Contrast sensitivity for different spatial frequencies

5.2.2.1. Stimuli and apparatus. Stimuli were sine wave gratings (Gabor patches, see Fig. 2.) with six different spatial frequencies [1, 2, 4, 8, 12, 16 cycles per degree (CPD)], which varied between blocks.

Stimulus presentation was controlled using the PsychoPy psychophysics software (Peirce, 2007) running on a PC. The graphics card was a Bits++ from Cambridge Research Systems facilitating 14 bits luminance resolution. Stimuli were displayed on a SONY Trinitron Multiscan G420, with a vertical refresh rate of 100 Hz, and the viewing distance was approximately 135 cm.

5.2.2.2. Procedure. The Detection task was a two interval forced choice procedure where participants had to detect in which temporal interval the Gabor patch had occurred. The Discrimination task was a single interval forced choice procedure where participants had to detect the orientation (horizontal or vertical) of the Gabor patch. Gabor contrast was modulated in each block with 0.1-log-unit-steps following a 3-up-1-down staircase procedure to determine the 79% threshold. The experiment was conducted in a dimly lit room and the participants were adapted to the light conditions in the room 5 min prior to commencing the experiment. All participants were exposed to a 20 trials training block to familiarize them with the paradigm, after which they conducted the six test blocks (one for each spatial frequency). In the Detection task, a trial was initiated by pressing space. There was a 300 ms delay before the first interval and an 800 ms delay between intervals. The intervals were displayed for 150 ms and a Gabor patch always occurred in one of the intervals, determined pseudo randomly. In this task observers had to report in which interval the Gabor patch had

[1] This reading test consisted of 250 words in total, of which 150 (50 per word length) were matched on important parameters, and are included in the present analyses.

[2] The data file for one of the controls in the reading task was corrupted, and another control (same age and education) was tested in the reading task only instead.

occurred with an unspeeded forced choice. In the Discrimination task, the procedure was identical except that only one interval occurred, and observers had to report if the orientation of the Gabor was vertical or horizontal.

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