



Patient assessment based on a theory of visual attention (TVA): subtle deficits after a right frontal-subcortical lesion

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Abstract

We report on a patient who complained of reduced awareness in the left visual field, but showed no visual neglect or extinction in clinical testing. By MR scanning, the brain damage was localized to the right basal ganglia, also involving structures in right frontal cortex. Using psychophysical testing and mathematical modeling based on Bundesen's theory of visual attention [TVA; Psychol. Rev. 97 (1990) 523], the patient's subjective experience of attentional disturbance was confirmed, and the deficit was specified into several components. At very short exposure durations, two effects were shown. The detection threshold was elevated, particularly in the left visual field, and stimuli in this side were given less attentional weight. In addition, the capacity of visual short-term memory (VSTM) was markedly reduced in both visual fields. The robustness of the test results was evaluated by bootstrap analysis. The study demonstrates the sensitivity and specificity gained by combining psychophysical testing with TVA modeling in the analysis of visual attention disorders. Extending the results of a pioneer study of parietal neglect patients by Duncan et al. [J. Exp. Psychol.: Gen. 128 (1999) 450], this study demonstrates the strength of the method in a single case, with a lesion outside parietal cortex, and only minor clinical symptoms.

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1. Introduction

Most studies of visual neglect and extinction have tested patients with marked clinical deficits. In this article, we introduce a method capable of describing patients who have only minor attentional problems. The method is based on Bundesen's theory of visual attention (TVA) [4–6]. TVA integrates a large part of the basic experimental research on attention [8], and accounts for findings from diverse paradigms such as single-stimulus recognition, whole report, partial report, detection, and visual search. A neurophysiological interpretation of TVA is underway [7], and the model has been integrated with theories of memory, categorization, and executive function [32,33]. Given its strength in the field of basic cognitive research, TVA should also be relevant to the clinical study of attention deficits. In a pioneer study, Duncan et al. [16] showed that the TVA model, in conjunction with tailored experiments, can indeed be used for accurate measurement of attention deficits. Duncan et al.'s choice of patients was typical for a study of attentional disorders: visual neglect patients with lesions involving the right posterior

parietal cortex. Using the experimental techniques of whole and partial report, Duncan et al. was able to estimate a range of central attention parameters in the patient group. Besides demonstrating the analytic specificity of their method, Duncan et al. also made some original observations. First, they showed that there was a large bilateral component to the supposedly "unilateral" neglect syndrome. The patients' storage capacity of visual short-term memory (VSTM), as well as their rate of visual encoding, was markedly reduced in both visual fields. Second, although the patients' sensory function was compromised, especially in the left visual field, selectivity for targets versus distractors was preserved. Encouraged by these findings, Duncan et al. urged for the method's application to other patient groups. The present study takes this request as its starting point.

Our study reapplied the experimental design developed by Duncan et al. [16], but extended the scope of their investigation. Instead of a group of parietal neglect patients, an in-depth study was made of a single patient with a lesion confined to frontal and subcortical structures in the brain. The patient showed no neglect in standard clinical tests, but still complained of reduced awareness of the left side. Accordingly, the aim of the study was to characterize this "subclinical" attention deficit and to explore the importance

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of anterior anatomical structures for the attentional parameters defined by TVA. To ensure reliable results from just one patient, we sought to improve Duncan et al.'s methodology on several points. To gain precise anatomical knowledge of the lesion, an MR scan of the patient's brain was made 16 months post-insult, at the same time as the experimental testing. Furthermore, to control for sensory loss, we included a perimetric investigation. Most importantly, in our TVA model fitting and theoretical discussions, we paid special interest to perceptual effects near stimulation threshold. This was not an issue in the article of Duncan et al., but proved to be an important refinement of their analysis.

The TVA model fitting procedure used to analyze the results was basically the same as that employed by Duncan et al. [16]. We refer to this article for mathematical details. However, as a new element we added a statistical meta-analysis: *bootstrapping* [18], to characterize the uncertainty related to each estimate produced by the model fitting. The bootstrap analysis provided information that is rarely available in psychological studies: a quantitative estimate of the reliability of each test result. To our knowledge, the method of bootstrapping has not been used for this purpose before in neuropsychological research (but see [1,3] for bootstrap analysis in neuroimaging). The mathematical details of the bootstrap analysis can be found in [Appendix A](#). To readers unfamiliar with TVA, the basic ideas of the theory are presented in the next section (see also [4] for a more detailed description and empirical support for the theory).

1.1. Theory of visual attention (TVA)

In TVA, attentional selection of a visual object x consists in encoding the object into visual short-term memory (VSTM). Objects in the visual field can be processed in parallel, and the objects that are selected (and, therefore, can be reported) from a briefly exposed visual display are those objects whose encoding processes complete before the sensory representation of the display vanishes and before VSTM has been filled up with other objects. Thus, objects in the visual field compete for encoding into VSTM, and the competition is a race. In normal subjects, the storage capacity of VSTM is limited to K objects, where K is about 4, so up to four objects can be reported from a brief display [34,52,53,57].

Consider, first, the processing of a stimulus display consisting of a single object x . Suppose x is displayed for t ms and immediately followed by a mask. In TVA, the time taken to encode x into VSTM is exponentially distributed. Specifically, the probability that object x gets encoded into VSTM equals

$$P_x = 1 - \exp[-v_x(t - t_0)]. \quad (1)$$

In [Eq. \(1\)](#), t_0 denotes the *minimal effective exposure duration*, below which information uptake from the display is assumed to be zero, and the equation presupposes that $t \geq t_0$. Typical estimates for t_0 are about 20 ms. The difference $(t - t_0)$ is the *effective exposure duration* of the stimulus

display; if the stimulus presentation had been unmasked, an additional effective exposure duration of μ ms should have been added to $(t - t_0)$. The rate parameter v_x can be described as the “speed” at which element x races toward VSTM. At $t = t_0$, v_x is the slope of the function relating the report probability P_x to the exposure duration t . When x is the only object in the visual field, v_x equals the *sensory effectiveness* of object x , s_x . The sensory effectiveness of an object depends on such factors as stimulus discriminability, contrast, and retinal eccentricity.

Both sensory effectiveness, s_x , and minimal effective exposure duration, t_0 , can be estimated from a curve showing how report probability P_x increases as a function of exposure duration t when object x is presented alone. The product of s_x and $(t - t_0)$ is the accumulated sensory effect (A_x) of object x at time t ,

$$A_x = s_x(t - t_0). \quad (2)$$

Some experimental designs, such as the partial report experiment in the present study, provide estimates for A_x without providing separate estimates for s_x and t_0 . In such cases, A_x may be taken as an indirect measure of sensory effectiveness if the effective exposure duration is kept constant.

Consider, next, the processing of a display consisting of multiple stimuli. In this case, the processing rate of object x (v_x) depends not only on the sensory effectiveness of object x (s_x) but also on the relative attentional weight of object x ($w_x / \sum_{z \in S} w_z$):

$$v_x = s_x \left(\frac{w_x}{\sum_{z \in S} w_z} \right). \quad (3)$$

As S denotes the set of all objects in the visual field, the relative attentional weight of object x is the attentional weight of x (w_x) divided by the sum of the attentional weights across all objects in the visual field ($\sum_{z \in S} w_z$).

In TVA, the *processing capacity*, C , for any given display is defined as the sum of all v values in the display:

$$C = \sum_{z \in S} v_z. \quad (4)$$

Thus, C is a measure of the total rate of information uptake (in objects per second). For displays consisting of objects with the same sensory effectiveness, s_x , [Eqs. \(3\) and \(4\)](#) imply that C is constant across variations in both the number of objects in the display and their attentional weights. Thus, when sensory effectiveness is kept constant, C may be regarded as a fixed total processing capacity divided among the different objects in the display, and the weight ratio $w_x / \sum_{z \in S} w_z$ may be regarded as that proportion of the total processing capacity C that is allocated to element x . When sensory effectiveness varies between objects in different parts of the visual field, separate estimates of processing capacity C (and storage capacity K) may be obtained for different parts of the visual field (e.g. for the left versus the right-visual hemifield). This procedure was used in our whole report experiment.

In some tasks (e.g. partial report), the subject is required to focus on target objects but ignore distractors. In order to perform such tasks efficiently, the attentional weights for targets should be higher than for distractors. The ratio (α) between the weight of a distractor ($w_{\text{distractor}}$) and the weight of a target (w_{target}) is a measure of the efficiency of selection:

$$\alpha = \frac{w_{\text{distractor}}}{w_{\text{target}}}. \quad (5)$$

An α value of 1 represents nonselective processing, whereas a value of 0 indicates perfect selection. If distractor and target weights are pooled across all positions, an α estimate pertaining to the whole display can be obtained. However, as with C and K , parameter α can also be estimated in separate parts of the visual field, if the pooling of weights is done over only the region in question.

2. General method

2.1. Participants

2.1.1. Case report

GL is a left-handed Caucasian woman, who was 34 years old at the time of testing. Before her brain injury, GL worked as an office assistant. She has corrected-to-normal vision. Twelve months prior to the examination reported in this study, in April 1999, GL had a cerebral hemorrhage. An acute CT scan showed damage in the region of the right sylvian fissure. An MR scan conducted five days later revealed that the right basal ganglia were also affected, and that a cavernous angioma in the right frontal region had caused the hemorrhage. Nine days after admission to the hospital, the angioma was resected, and the artery closed with metal clips. Post-operative recovery was uncomplicated, although initially characterized by fluctuating awareness. Neuropsychological examination one month post-insult revealed moderate cognitive deficits, affecting the domains of memory, concentration, psycho-motoric tempo, and executive functioning. Impaired insight was also noted. In addition, GL's motor function was compromised by a mild strength reduction in the left arm, and also from a congenital strength reduction in the right arm. However, there were no signs of aphasia, and visual problems were not reported.

Five months later, GL was accepted for an intensive rehabilitation program at the Center for Brain Injury Rehabilitation in Copenhagen. The initial neuropsychological examination at the Center generally confirmed the above mentioned deficits, although insight was improved. In the period from February to May 2000, GL participated in a full-time rehabilitation program. During the last month of this program, she was also tested in the present study. At the end of the rehabilitation program, a neuropsychological report concluded that the above mentioned cognitive problems persisted to a moderate degree (see testing scores in Table 1). In particular, problems concerning executive

Table 1
GL: neuropsychological test scores

Digit span forwards	5
Digit span backwards	3.5
Corsi block tapping forwards	5.5
Corsi block tapping backwards	3.5
Trail making A (s)	41
Trail making B (s)	88
Digit symbol	39
Mesulam letter cancellation (s)	190, one error (lower left quadrant)
Mesulam figure cancellation (s)	116, one error (lower left quadrant)
Street completion test	18/20 correct

function had been noted during the rehabilitation program, including a tendency to work haphazardly and uncorrected. GL was able to concentrate well for a single task, but had difficulty at managing more complex situations. However, visual or visuo-constructive problems were not found. In particular, in the course of several neurological and neuropsychological examinations, GL had not been shown to suffer from visual neglect (even on the demanding Mesulam cancellation tests). Neither did she have hemi- or quadrantanopsia, which we tested for using a perimetry program developed by Kasten et al. [28,29]. In spite of this, she occasionally complained of reduced awareness of left-side stimuli, for example when moving about in city traffic.

In relation to the present study, GL was MR scanned (in August 2000, 16 months post-insult) using a 1.5 T scanner. The scan showed a lesion involving both frontal and subcortical structures in the right side of the brain. In Fig. 1, GL's brain is shown (from top to bottom) in sagittal, transversal, and coronal views, and the location of the lesion is indicated by arrows. The sagittal and coronal images were acquired using a T1-weighted sequence, and the transversal image was acquired with a T2-weighted sequence. In the transversal and coronal slices, the left side represents the right hemisphere (marked by "R"). The scan shows a combination of hemorrhage sequela and damage secondary to the neurosurgical resection of the angioma. Damage related to the bleeding is centered in an area located by the head of the caudate nucleus, also affecting parts of the internal capsule and the putamen (see sagittal and coronal views). By the medial frontal gyrus and the upper part of the inferior frontal gyrus, an operation cavity protrudes into a subcortical area of cavity, hemorrhage sequela, and metal clips (see transversal view). Around the operation cavity and the hemorrhage, there is a small brim of gliosis changes in the white matter. In summary, GL's lesion was confined to the right side of the brain, and involved both the anterior basal ganglia and the immediately overlying white matter and frontal gyri.

2.1.2. Control group

Eight neurologically healthy control participants (six females, two males) were also tested. The control participants were matched to GL for age (mean age: 31 years, range: 27–42 years). All participants in the control group

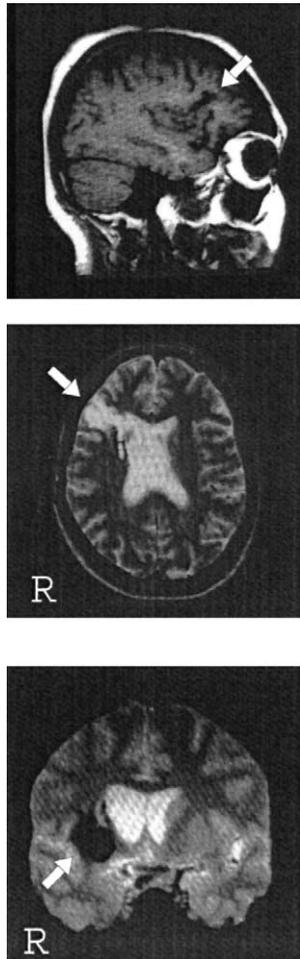


Fig. 1. MR scan of GL's lesion.

had normal or corrected-to-normal vision. None of the participants had any previous experience with tests involving recognition of briefly presented stimuli. They were paid for their participation.

2.2. Stimuli and general design

Before the experiments, informed consent according to the Declaration of Helsinki II was obtained from all participants. The experimental program consisted of whole report, partial report, and color report. The experiments were designed according to the description in Duncan et al. [16]. All participants completed the elements of the program in the same sequence. Testing was divided into sessions of 30–45 min and completed in 11–14 sessions per participant, scheduled within three months. All testing sessions were run by the same experimenter. At the end of the experimental program, all participants were given neuropsychological tests, including Mesulam cancellation tests for visual neglect. In addition, computer perimetries [28,29] were conducted.

The experiments were conducted in a semi-darkened room at the Department of Psychology, University of Copenhagen.

They were run on an IBM-PC compatible computer with a VGA monitor. The refresh rate was usually 100 Hz, but in some cases adjusted to 60, 90, or 120 Hz to obtain specific exposure times. The distance between the monitor and the eyes of the subject was approximately 70 cm. At the beginning of each experiment, participants were given a standardized instruction, repeated when needed during practice trials. The requirement of central fixation at the start of each trial was strongly emphasized. In initial sessions, eye movements were monitored by the experimenter. As no problems were detected for any participant, including GL, the importance of central fixation was simply repeated at regular intervals during the remaining sessions. In general, when compliance with the fixation instructions was directly tested, it appeared to be excellent, and no findings from the experiments suggested any failures to obey the instructions.

When the participant said “Cross!” (indicating fixation on the central fixation cross), the display was initiated with a button press by the experimenter. The fixation cross disappeared immediately, and following a 100 ms gap, the stimulus letters were displayed for a prespecified exposure time. Letters were either red or green, with colors selected for approximately equal reportability. The luminances of the red and green colors were 2.1 and 3.9 cd/m², respectively. The letters were shown on a black background. Vertically every letter subtended 0.7° of visual angle. In each trial, letters were drawn without replacement from the set ABEFHJKLMNPRSTWXYZ. The display was either followed by an empty black screen or a pattern mask exposed for 500 ms. The mask consisted of separate, white characters, one in each possible display location. Each mask character consisted of an open square, 0.75° in height, inside which all 18 stimulus letters were superimposed.

Following the display, the participant reported the letters she/he was “fairly certain” of having seen. Guessing was discouraged. Responses were nonspeeded, and letters could be reported in any order. The report was then typed into a computer by the experimenter. Trials were given in blocks of 24 (whole and color report) or 32 (partial report). A typical experimental session consisted of 5–7 testing blocks after an unscored warm-up block. If the number of erroneously reported elements exceeded 3 or 4 in a block, indicating too liberal reporting criteria, the participant was instructed to be more cautious. The proportion of erroneous responses (intrusion errors) was generally low (around 5–10%), and similar between GL and the control group. To avoid fatigue, not more than 300 trials were conducted in one session, and sessions were always scheduled on different days. To control for practice effects, all subjects completed approximately the same number of trials. However, apart from improvement in the initial practice sessions, practice effects on performance were negligible. The full experimental program consisted of 1360 scored trials plus about 500 unscored trials for warm-up and calibration of individual exposure times (due to an error of administration, GL did 24 trials more than scheduled in whole report and 24 fewer in color report).

3. Experiment 1: Whole report

TVA assumes that visual attention distributes a limited pool of processing resources over the visual field. Accordingly, a logical first step in investigating attentional function is to estimate the amount of available processing capacity. Whole report is a classical experimental procedure for the study of attentional capacity [8,52,53]. The procedure provides estimates of the total amount of information that can be perceived from a brief visual display as a function of exposure duration. Perception is measured by nonspeeded verbal report. In the context of TVA analysis, whole report permits estimation of two central parameters of attentional capacity: the rate of visual encoding, C , and the storage capacity of visual short-term memory, K . In addition, a third parameter is estimated: t_0 , the minimal effective exposure duration or perception threshold. This parameter did not receive special interest by Duncan et al. [16], but the present study demonstrates its neuropsychological significance. Since GL had a unilateral lesion and complained of attention problems in one side of the visual field, her attentional capacity (as well as t_0) was estimated separately on the left and right.

3.1. Method

In each trial, a column of five equally spaced letters was displayed. The column was centered on the horizontal meridian and measured 7.5° vertically. The center of the column was located 3.3° either to the left or right of fixation. Letters were either all red or all green, the color shifting every 10 trials. The participant was instructed to name as many as possible (see Fig. 2).

Three different exposure durations were used for each participant. Individual exposure durations were selected to characterize both the early and the late part of the participant's whole report function. To avoid eye movements, the longest exposure duration was set to 200 ms for all participants. However, performance was not expected to reach the maximum capacity of the participant's visual short-term memory with effective exposure times below 300–400 ms. Therefore, half of the displays were unmasked, resulting in a longer effective exposure duration due to the afterimage effect. TVA assumes that the prolongation, μ , is constant across exposure conditions; μ is typically estimated at a few hundred milliseconds. The two shortest exposure durations varied from participant to participant and were calibrated in an initial practice session. The lowest exposure duration was set just

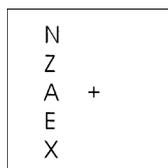


Fig. 2. In whole report, a column of five letters was flashed either to the left or right of fixation.

above the participant's perceptual threshold t_0 (i.e. the exposure duration at which the score dropped to zero). The second exposure duration was intermediate between the other two, but closer to the lowest value to capture the early, sharp rise in the whole report function. This way, the letter column was shown under 12 different conditions: 2 sides \times 3 exposure durations \times 2 mask conditions. Every trial type occurred twice in each block, in random order. Overall, 40 trials were conducted per experimental condition (by an error of administration, patient GL performed 42 trials per condition). GL's three exposure durations were set at 60, 120, and 200 ms. For each of the eight control participants, the three exposure durations were set in the range 30–50, 90–100, and at 200 ms, respectively.

3.2. Results

The TVA fits to the observed probabilities in each of the 12 experimental conditions were fairly close. For GL, the Pearson product-moment correlation coefficient, r , between observed and predicted probabilities was 0.96, and for participants in the control group, the average r was 0.95 (range: 0.92–0.98). Fits could probably be improved by running more trials per condition [50], but still, very clear results emerged. The performances of GL and a typical control participant (SW) are shown in Fig. 3.

Both GL and the participants in the control group exhibited a qualitative pattern of performance known from other whole report studies [9,16,50,52]. Below a certain minimal effective exposure duration, t_0 , no letters were reported. Above this exposure duration, the curve rose sharply, gradually flattening out over the course of a few hundred milliseconds. Given long enough exposure time, performance seemed to approach an asymptotic value, usually interpreted as the maximum storage capacity of visual short-term memory [54]. While showing this familiar pattern, Fig. 3 also exemplifies the striking quantitative difference between GL and the control participants. For GL, the whole report function began its ascent at a later point (especially in the left side), the slope was more shallow, and the asymptotic value was lower. These deficits were accurately captured by the parameter estimates shown in Table 2.

The standard errors of each estimate, as revealed by the bootstrap analysis of the fits (cf. Appendix A), are also shown in Table 2. These figures permit an evaluation of the reliability of each test result. The bootstrap analysis indicated that the fits were robust. For example, the standard errors related to GL's K estimates were less than 0.1, and the standard errors of GL's C estimates were in the range of $1\text{--}2\text{ s}^{-1}$. Fig. 4 shows how the bootstrap estimates of GL's C_{right} value were distributed. The bootstrap estimates were close to normally distributed around the C value found in the original fit, 14 s^{-1} , with a fairly small variance. In general, the distributions of bootstrap estimates of the parameters approached normal distributions as the number of bootstrap repetitions was increased.

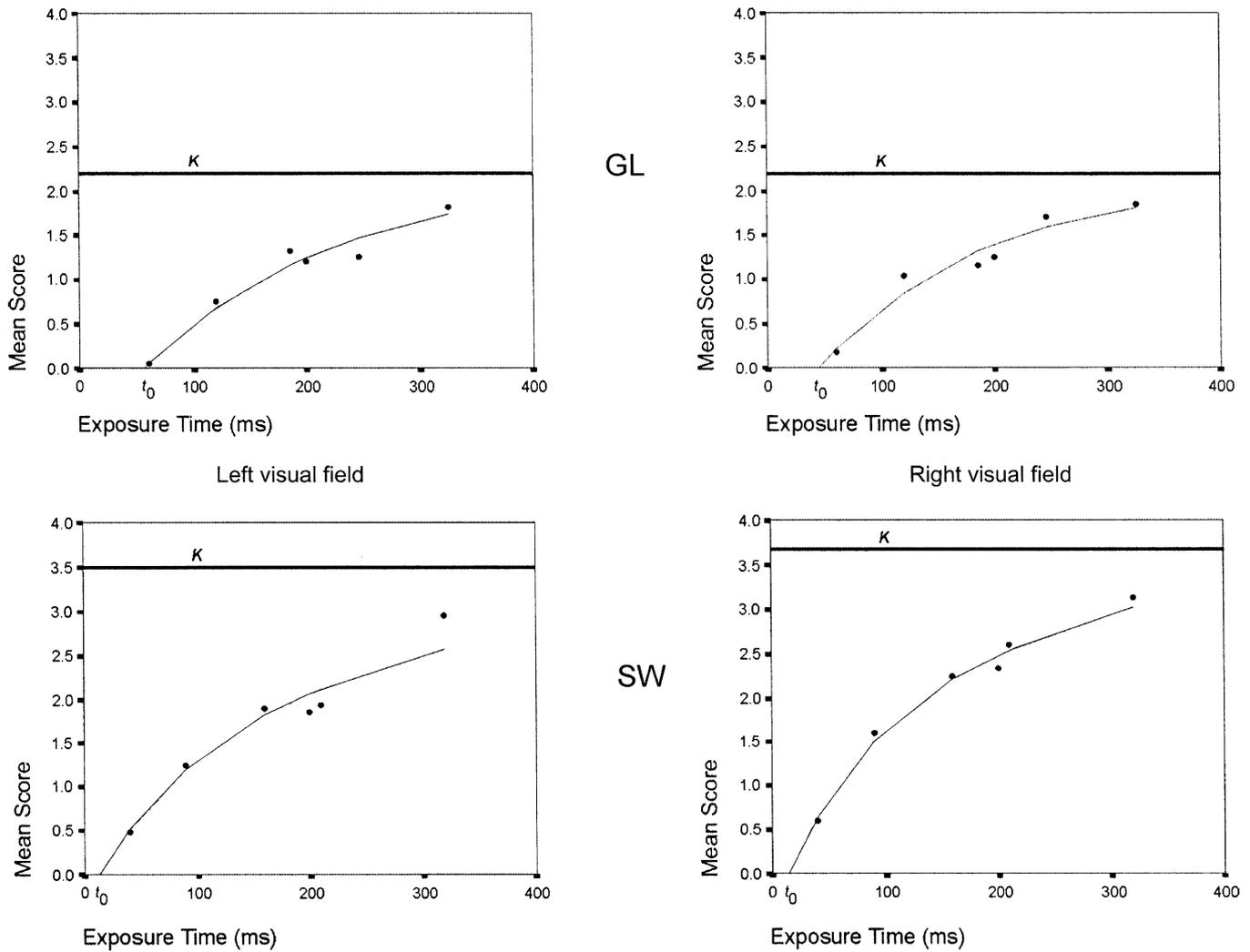


Fig. 3. Whole report performance for patient GL (upper panels) and a typical control participant SW (lower panels). Each panel shows the mean number of correctly reported letters as a function of exposure duration, separately for the left (left panels) and right (right panels) visual fields. Solid curves represent maximum likelihood fits to the observations. Estimates of visual short-term memory capacity K are marked by a horizontal line, and t_0 denotes the visual threshold.

Table 2
Whole report: model parameters

Participant	K_{left}	K_{right}	C_{left}	C_{right}	$t_{0\text{left}}$	$t_{0\text{right}}$	μ
Patient							
GL	2.2 (0.08)	2.2 (0.07)	12 (1.2)	14 (1.5)	56 (3.1)	44 (7.9)	126 (17)
Controls							
MT	3.4 (0.07)	3.5 (0.10)	25 (2.2)	22 (1.8)	2 (4.0)	1 (4.4)	148 (14)
SW	3.5 (0.15)	3.7 (0.16)	21 (2.3)	29 (3.4)	13 (7.1)	14 (5.5)	120 (16)
KH	3.2 (0.16)	3.5 (0.16)	36 (6.6)	33 (2.8)	41 (6.5)	45 (1.9)	119 (14)
IH	3.3 (0.36)	3.3 (0.25)	14 (2.3)	14 (1.1)	4 (6.8)	2 (4.7)	165 (15)
CB	3.2 (0.31)	3.5 (0.15)	16 (1.8)	16 (1.3)	36 (5.7)	33 (3.7)	152 (14)
CP	3.9 (0.12)	4.0 (0.07)	16 (1.2)	19 (1.5)	0 (4.7)	5 (5.4)	168 (15)
AL	4.5 (0.36)	4.8 (0.30)	29 (2.5)	32 (2.5)	30 (4.0)	28 (3.5)	129 (10)
AN	2.4 (0.08)	2.7 (0.13)	17 (1.6)	16 (1.5)	1 (4.0)	5 (5.0)	127 (17)

Note— K_{left} , K_{right} : visual short-term memory capacity (number of elements) measured in left- and right-visual fields, respectively; C_{left} , C_{right} : total processing rate (elements/s) measured in left- and right-visual fields; $t_{0\text{left}}$, $t_{0\text{right}}$: minimum effective exposure duration (ms) in left- and right-visual fields; μ : additional effective exposure duration for unmasked displays (ms). Standard errors of each estimate are given in parentheses (as estimated by 200 bootstrap repetitions).

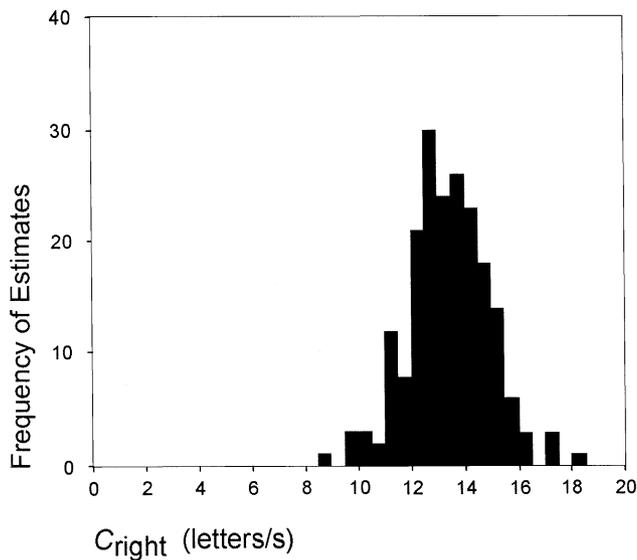


Fig. 4. Distribution of estimates for patient GL's C_{right} parameter obtained by bootstrapping.

To decide whether the parameter estimates for GL differed significantly from estimates for the controls, statistical analyses were made. In the control group, the average value of K_{left} was 3.4, and the average value of K_{right} was 3.6 (S.D. = 0.6 in both cases). These values agree well with previous estimates of the capacity of visual short-term memory in young subjects [50,52,57]. Furthermore, the K_{left} and K_{right} values were similar for each participant: the Spearman's rank correlation coefficient, r_S , was 0.88, $P < 0.01$. Thus, for each control participant, the capacity of visual short-term memory was nearly the same in the two visual fields. In the case of GL, the K_{left} and K_{right} values were very nearly identical to each other. However, GL's K_{left} and K_{right} values were 2.0S.D. and 2.4S.D. below the control group mean, respectively. Furthermore, GL's K_{left} and K_{right} values fell below the values of every control participant (in either case, $P < 0.01$ by a one-tailed binomial test). Thus, the capacity of GL's visual short-term memory was markedly reduced for stimuli in both visual fields.

In the control group, C_{left} and C_{right} values averaged 22 and 23 s^{-1} , respectively. The values of C_{left} and C_{right} were strongly correlated across participants: $r_S = 0.92$, $P < 0.01$. As with the K values, symmetric capacity in the two visual fields was indicated. The C_{left} estimate of GL was lower than her C_{right} estimate, but just as in the control group, the difference was small. GL's C_{left} estimate was below every control participant's ($P < 0.01$ by a one-tailed binomial test), and only control IH had a lower C_{right} estimate than GL ($P < 0.05$ by a one-tailed binomial test). However, the variabilities of both C_{left} and C_{right} were quite high in the control group. Therefore, the C_{left} and C_{right} values of GL deviated only 1.3S.D. and 1.1S.D., respectively, from the mean of the control group. Although being at the low end of the nine estimates, GL's C values were only moderately reduced.

In the control group, the mean values of $t_{0\text{left}}$ and $t_{0\text{right}}$ were 16 and 17 ms, respectively (S.D. = 17 ms in both cases). GL's $t_{0\text{left}}$ value was 2.3S.D. above the control group mean, and her $t_{0\text{right}}$ value was 1.6S.D. above the mean. Furthermore, $t_{0\text{left}}$ was higher for GL than for any of the eight control participants ($P < 0.01$ by a one-tailed binomial test), and $t_{0\text{right}}$ was higher for GL than for seven out of the eight controls ($P < 0.05$). Thus, GL's visual threshold clearly was elevated in both sides.

In the control group, the two t_0 values were highly correlated across participants ($r_S = 0.80$, $P < 0.01$), and the absolute value of the difference between an individual's t_0 values was on average only 2.8 ms (S.D. = 1.5 ms). In contrast, the difference between GL's two t_0 values was 12 ms. This difference should be evaluated in light of the (bootstrap) standard errors related to GL's estimates of $t_{0\text{left}}$ and $t_{0\text{right}}$: 3.1 and 7.9 ms, respectively. By a one-tailed t -test (d.f. = 200), the difference between GL's two t_0 values just failed to reach significance ($P = 0.08$). In conclusion, GL's visual threshold was generally elevated, but with a nonsignificant tendency towards a higher threshold in the left visual field.

Judging from the parameter estimates of C , K , and t_0 , lateral differences in the control group were small and inconsistent across participants. However, analysis of the 3840 "raw" reports revealed a small, systematic difference between visual fields. For control participants, the average score in the right hemifield was 1.87, compared with 1.73 in the left hemifield. Due to the large number of observations, the difference was highly significant ($P < 0.001$). The finding is consistent with previous studies showing a slight left hemisphere advantage for perception of letters [30]. However, since we are dealing with raw scores, it is not possible to say whether the minor lateral asymmetry was related primarily to speed of processing (C), capacity of visual short-term memory (K), or minimal effective exposure duration (t_0).

3.3. Discussion

3.3.1. The neural basis of VSTM deficits

The whole report experiment revealed a large, bilateral reduction of visual short-term memory capacity in GL. Compared to the normal capacity of 3–4 items, GL could encode and retain only about two items simultaneously. The finding is similar to that of Duncan et al. [16], who found reduction of VSTM capacity in a group of parietal neglect patients. Duncan et al. suggested that reduction in VSTM capacity is a component of the neglect syndrome. This conclusion is in agreement with a preliminary report by Peers et al. [40], which suggests that in case of damage to the posterior cortex, VSTM deficits occur less frequently after superior parietal lesions than after damage to the inferior parietal and superior temporal cortex. Neglect has been related to both the inferior parietal lobe [55] and the superior temporal gyrus [27]. However, GL did not have neglect, and her lesion did not involve the posterior part of the cortex. This indicates that VSTM deficits may also,

besides being related to parietal and temporal lesions, result from other types of brain damage. In particular, the study of GL points to the importance of the right basal ganglia and the immediately overlying white matter and frontal gyri for the capacity of VSTM. However, the finding also makes clear the need for more studies of VSTM capacity in patients with damage to the anterior parts of the brain.

3.3.2. *The merit of whole report*

In their investigation of VSTM capacity in normal subjects, Vogel et al. [57] criticized the method of whole report. They argued that whole report does not provide a pure estimate of VSTM capacity since it relies on verbal report of the visual memory trace. Whole report estimates of VSTM capacity could therefore include contributions from both verbal and visual memory systems, thereby inflating the estimate. On the other hand, it is also possible that the verbal recoding might not carry over all items in VSTM, thus leading to artificially low estimates of VSTM capacity. Instead Vogel et al. used match-to-sample tests, which do not require a verbal recoding operation. Whereas the criticism of Vogel et al. seems valid in principle, it does not affect the conclusions of the present study. Control subjects had K estimates around 3–4 objects, which is closely in line with the results found by the alternative method of Vogel et al. Thus, it seems that the added requirement of verbal recoding did not alter VSTM estimates. As for the demonstration of a marked VSTM deficit in GL, this finding also seems robust. GL was not aphasic and should have had no more difficulty with verbal recoding of the visual impression than control subjects. Also, her verbal short-term memory span was so large (five items) that limitations in this store cannot account for the fact that she could report only about two items from the visual display. It should also be mentioned that our whole report method has an important advantage over the match-to-sample test used by Vogel et al.: our whole report experiments provide much more information about the encoding process, especially its time course. This permits estimates of important attentional variables related to VSTM, such as C and t_0 .

3.3.3. *Bilaterality of attentional deficits*

One of the remarkable findings of Duncan et al. [16] was that, even though their neglect patients had a clear, lateralized attention disorder, the reduction of VSTM capacity was strictly bilateral. As this article will make clear, GL also had a lateralized attention disorder, albeit more subtle. In this sense, her bilateral VSTM deficit can be seen as a replication of Duncan et al.'s finding. On the basis of the present evidence it may be hypothesized that damage to VSTM is typically nonspecific, reducing capacity uniformly in the visual field.

Turning to C , GL's rate of visual encoding was only moderately reduced. Although the mean value of C was lower for GL than for any of the eight controls, the reduction in C was modest considering the large variability in the control group. Also, GL's C values were almost the same to

the left and right. It seems that GL's rate of visual encoding, although generally low, was not specifically reduced in the left side. This symmetry was surprising, given her complaints of attention problems in the left side. However, near the temporal threshold for perception t_0 , the results indicated a lateralized deficit. Whereas control participants had practically identical values in the two visual fields, GL's t_0 value was 12 ms higher in the left visual field, representing a 27% increase. With her C and K values close to identical in both sides, GL's symmetrical performance in the whole report experiment seemed to break down at exposure times near threshold. However, the effect failed to reach significance. To investigate GL's near-threshold performance more thoroughly, the partial report experiment introduced more experimental conditions at very short exposure durations.

4. Experiment 2: Partial and color report

In the investigation of attentional function, partial report forms the natural complement of whole report. Whereas whole report estimates the total attentional capacity, partial report measures how this capacity is distributed across objects in the visual field. In TVA, this corresponds to the concept of *weighting*. In the partial report experiment, two aspects of attentional weighting were estimated: the *task-related* weighting of objects designated as either targets or distractors and the *spatial* weighting of objects in each of the four visual quadrants.

In TVA the probability of perceiving an object depends not only on its relative attentional weight but also on the sensory effect of the object (accumulated during the effective exposure duration). To obtain measures of sensory effects (independent of attentional weighting) in separate parts of the visual field, the partial report experiment included conditions in which only one stimulus was presented. Extending this investigation of basic sensory function, a color report experiment was also included. This experiment estimated sensory effects of color, instead of letter identity, in each of the four visual quadrants. Since targets and distractors in the partial report experiment were defined by color, it was necessary to determine whether a lack of discrimination was due to sensory rather than attentional deficits.

In partial report, we chose to study not only left–right differences, but also differences between the upper and lower parts of the visual field. Visual neglect has been reported to be more severe below the horizontal meridian [21,31,47], and we wanted to investigate whether this effect was also present in a patient with subtle attention problems such as GL.

4.1. *Method*

4.1.1. *Partial report*

The partial report experiment comprised 40 testing blocks. Each testing block consisted of two subblocks of 16 trials

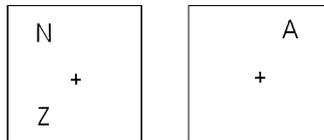


Fig. 5. In partial report, either one or two letters were flashed in separate quadrants. Target stimuli were distinguished from distractors by color (red vs. green).

each, one subblock for each of the two target colors (red and green). Preceding each subblock, a rectangle in the target color was displayed. Participants were given 5–10 s to memorize the target color before continuing the experiment. Letters were then presented at the corners of an imaginary square of $5.0^\circ \times 5.0^\circ$, centered on fixation. The participant was required to name as many target-colored letters as possible, ignoring distractors. Either a single target, a target accompanied by a distractor, or two targets were displayed (see Fig. 5). When two letters were displayed, they were always arranged in a row or column. Overall, each subblock contained one example of each of 16 trial types: target appearing alone in each position (four displays), accompanied by a distractor on the same or opposite side (eight displays, four column and four row), and accompanied by another target on the same or opposite side (four displays, two column and two row). The sequential order of the 16 types of trials was randomized independently for each subblock. The 16 trial types covered 20 experimental conditions: for each of the four trial types with two targets, performance could be separately analyzed for each of the two targets. This way, five conditions for each of the four stimulus locations were produced: target alone, target accompanied by a distractor in same or opposite side, and target accompanied by a target in same or opposite side.

Only one duration of stimulus exposure was used for each participant, and stimulus exposures were immediately followed by masks. The exposure duration was set in an initial practice session, aiming for 75% correct on trial types with a single target. In the actual experiment, GL scored 79% in these trial types, whereas the mean score of the control group was 78% (range: 54–88%). GL's exposure duration was set at 60 ms, and the exposure durations for control participants SW, CP, MT, IH, KH, AN, AL, and CB were 33, 33, 33, 40, 40, 44, 50, and 60, respectively.

4.1.2. Color report

Display locations were the same in color report as in partial report, but only one letter (randomly red or green) was shown in each trial. The participant was instructed to name the color of the letter, ignoring its identity. Four experimental conditions, one for each of the possible stimulus locations, were used. Sixty trials were run for each of the four conditions, and testing was organized in 10 blocks, each consisting of 24 trials (due to an error of administration, GL did only none testing blocks, i.e. 54 trials per condition). The sequential order of the four trial types was randomized

independently for each testing block. As in partial report, a post-masked, individually set exposure duration was calibrated in a practice session, aiming for 75% correct. In the actual experiment, patient GL scored 62%, whereas participants in the control group scored 70% on average (range: 60–88%). For most participants, the exposure duration was slightly briefer than in partial report. GL's exposure duration was set at 40 ms, and the exposure durations for control participants SW, CP, MT, IH, AN, KH, AL, and CB were 30, 30, 30, 30, 33, 40, 40, and 50, respectively.

4.2. Results

4.2.1. Partial report

An initial, qualitative impression of the partial report results can be gained from some graphical illustrations. Fig. 6 shows the mean scores in each experimental condition, pooled across upper and lower visual fields to bring out left–right differences in performance. The two upper bar charts show the performance of the control group. Scores were very similar in the two visual fields, and the basic pattern of performance replicated that of earlier partial report studies [10,14]. The score was maximal when the target was presented alone. If the target was accompanied by a distractor, performance showed some decline. If the target was accompanied by a second target, the score decreased considerably. The decrements appeared to be stronger when the target was accompanied by a stimulus on the same side than when the target was accompanied by a stimulus on the opposite side.

GL's performance also conformed to this pattern, with distractors causing some score decrement, but targets more so. However, unlike the nearly symmetrical performance of the control group, GL had marked differences between the left- and right-visual hemifields. Targets presented alone were much less reliably perceived in the left visual field. Furthermore, perception of right-sided targets was not much affected by distractors or targets in the left visual field. Performance was nearly the same under these conditions as for singly presented targets on the right. In contrast, the perception of left-sided targets was subject to considerable distraction from stimuli in both left- and right-visual fields.

The vertical pooling of scores in Fig. 6 masks an important difference between the upper and lower visual fields. Fig. 7 shows the complementary, horizontal pooling of scores across the left- and right-visual fields. Two things are noteworthy in Fig. 7. The first is the similarity between GL's performance and that of the control group. As measured on the vertical dimension, GL had a normal pattern of response. The second interesting aspect of Fig. 7 is the general difference between scores in the upper and lower visual field. Single targets were perceived a little less reliably in the lower visual field. More importantly, perception of targets in the lower visual field was markedly disturbed by items in the upper field.

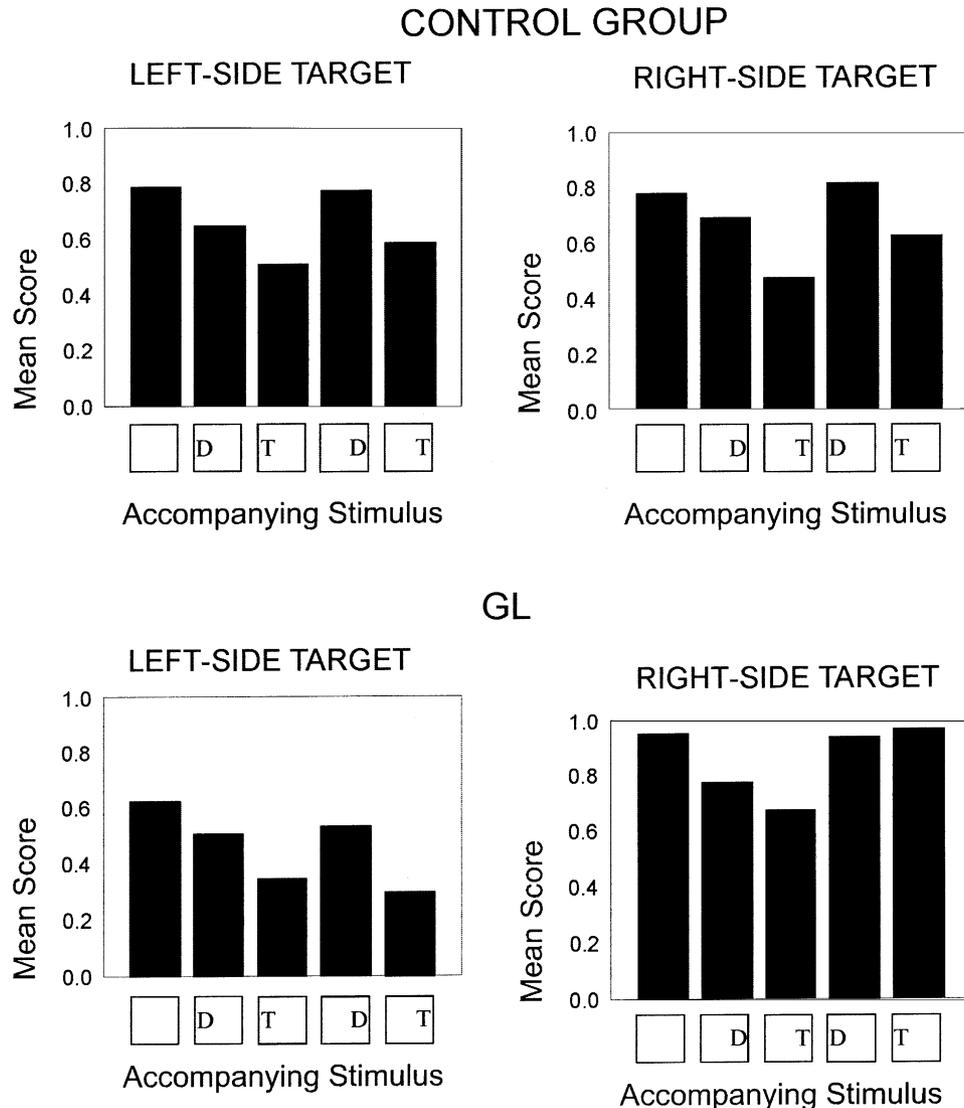


Fig. 6. Vertically pooled mean scores in each condition of the partial report experiment for the control group (upper panels) and patient GL (lower panels). Each bar represents the mean score in one of 10 conditions: target presented alone in the left visual field, accompanied by a distractor (D) in the left field, by a target (T) in the left field, by a distractor in the right field, or by a target in the right field, respectively; and vice versa for targets in the right-visual field. Each bar represents the mean of 640 observations (for the control group) or 80 observations (for GL).

Taken together, Figs. 6 and 7 suggest that two independent factors influenced the performance of GL: a bias for upper-field stimuli, which was shared by the control group, and an additional bias for right-sided stimuli, which was unique to GL. As in the whole report experiment, this qualitative pattern was described quantitatively by TVA modeling. The modeling produced individual estimates of target weights and sensory effects (accumulated during the effective exposure duration) in each of the four visual quadrants. In addition, the efficiency of top-down selection (measured by parameter α , the attentional weight of a distractor divided by the weight of a target in a given position) was estimated in left- and right-visual fields. As in whole report, the model fitted the observed data closely. The mean correlation between observed and theoretically fitted scores

was $r = 0.91$ in the control group (range: 0.78–0.97) and $r = 0.98$ in the case of GL. However, unlike the whole report experiment, the estimated A and w parameters were not directly comparable between participants. This is due to the fact that only one, individually set, exposure duration was used for each participant. A values can be corrected for individual variations in exposure time by dividing with $(t - t_0)$ in each case, yielding directly comparable s values (cf. Eq. (2)). However, a participant's t_0 value cannot be determined from performance with a single exposure duration, nor can the individual t_0 estimates obtained in whole report be transferred, as t_0 values depend on the specific physical properties of the experimental display. Thus, the s values could not be determined exactly to allow direct comparison of sensory effectiveness between participants. As for the w

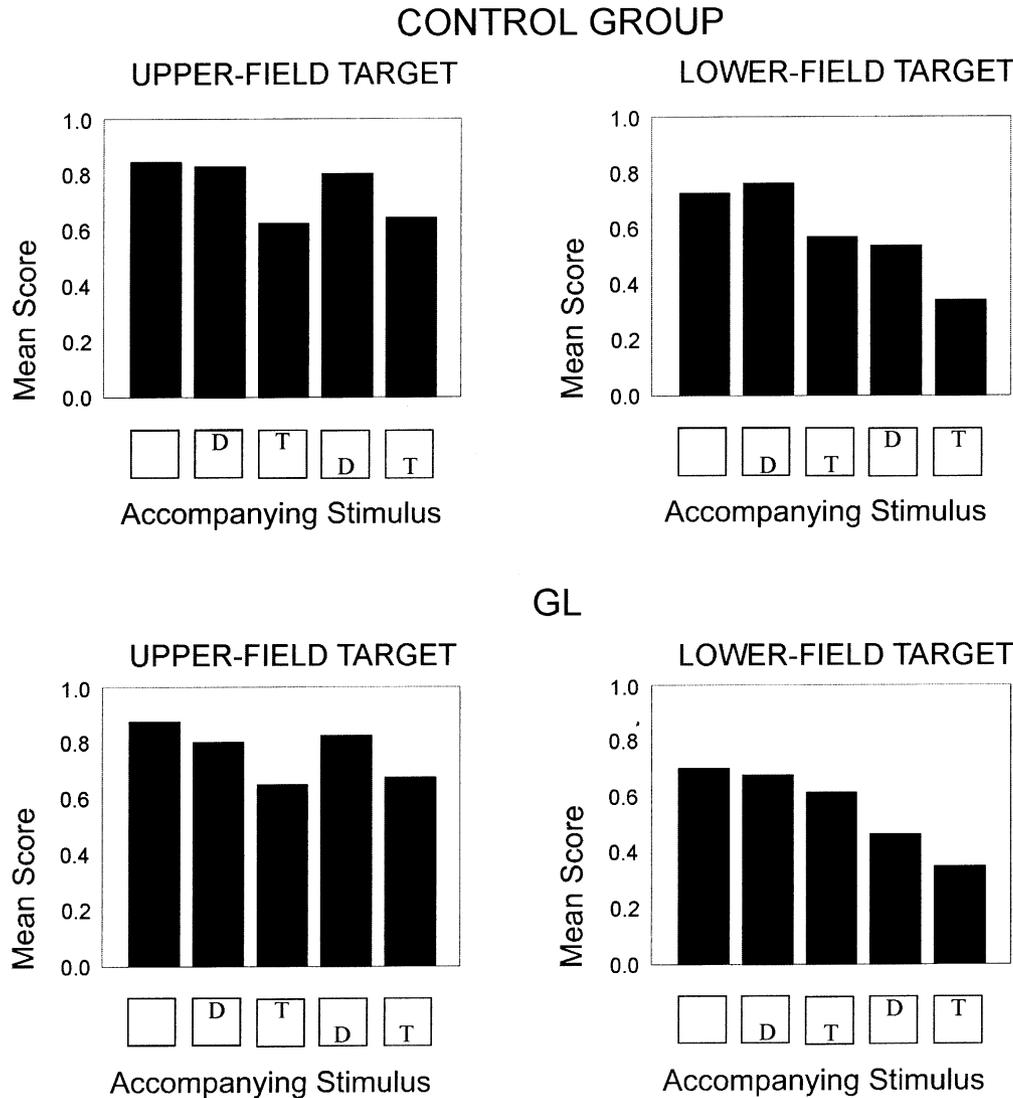


Fig. 7. Horizontally pooled mean scores in each condition of the partial report experiment for the control group (upper panels) and patient GL (lower panels). Each bar represents the mean score in one of 10 conditions: target presented alone in the upper visual field, accompanied by a distractor (D) in the upper field, by a target (T) in the upper field, by a distractor in the lower field, or by a target in the lower field, respectively; and vice versa for targets in the lower visual field. Each bar represents the mean of 640 observations (for the control group) or 80 observations (for GL).

estimates, absolute attentional weights have no meaning in TVA. Therefore, only relative, intra-individual patterns of performance (e.g. bias to the left versus right, top versus bottom) could be compared between participants.

To quantify these differences, a number of indices were computed from the “raw” A and w estimates in the four positions. The first of these was the *laterality* index, $A_{lat} = A_{left}/(A_{left} + A_{right})$, where A_{left} denotes the mean of the A values in the left upper and lower visual field, and A_{right} is similarly defined for the right-visual field. A_{lat} is as a measure of lateral differences in sensory effects (accumulated during the effective exposure duration). A_{lat} values above 0.5 indicate stronger sensory effects in the left visual field, whereas values below 0.5 represent better function to the right. Similarly, a *verticality* index for the sensory effects in

upper versus lower visual fields was computed by the formula $A_{ver} = A_{upper}/(A_{upper} + A_{lower})$. Here, A_{upper} and A_{lower} denote the means of A values in the upper and lower visual fields, respectively. Laterality and verticality indices for the attentional weights were similarly computed (for each of the four visual quadrants, the attentional weight was defined as the sum of the weight of a target and the weight of a distractor in the quadrant). The results are shown in Table 3, together with the estimated α values in the left and right side. The standard errors of the estimated parameter indices and α values are also given (as estimated by 200 bootstrap repetitions). As can be seen from the table, the estimates of A indices were robust, with bootstrap standard errors at 10% or less of the estimated index value. The accuracy of the w indices also seemed quite high. The uncertainty related to

Table 3
Partial report: model parameters

Participant	A_{lat}	A_{ver}	w_{lat}	w_{ver}	α_{left}	α_{right}
Patient						
GL	0.26 (0.03)	0.53 (0.05)	0.31 (0.06)	0.82 (0.06)	0.32 (0.11)	0.22 (0.27)
Controls						
SW	0.48 (0.02)	0.55 (0.03)	0.52 (0.05)	0.69 (0.05)	0.31 (0.12)	0.00 (0.08)
CP	0.56 (0.04)	0.62 (0.04)	0.57 (0.07)	0.78 (0.05)	0.51 (0.15)	0.34 (0.24)
AN	0.49 (0.03)	0.55 (0.03)	0.33 (0.08)	0.74 (0.09)	0.23 (0.09)	0.00 (0.03)
MT	0.47 (0.02)	0.50 (0.03)	0.50 (0.07)	0.50 (0.10)	0.00 (0.04)	0.00 (0.03)
IH	0.52 (0.03)	0.66 (0.03)	0.71 (0.07)	0.87 (0.05)	0.28 (0.10)	0.00 (0.11)
CB	0.51 (0.03)	0.53 (0.04)	0.58 (0.06)	0.47 (0.10)	0.00 (0.06)	0.07 (0.09)
AL	0.50 (0.03)	0.53 (0.03)	0.46 (0.06)	0.66 (0.07)	0.23 (0.10)	0.00 (0.06)
KH	0.48 (0.04)	0.58 (0.04)	0.47 (0.10)	0.86 (0.07)	0.35 (0.20)	0.57 (0.43)

Note— A_{lat} : laterality index of sensory effect; A_{ver} : verticality index of sensory effect; w_{lat} : laterality index of attentional weighting; w_{ver} : verticality index of attentional weighting; α_{left} : effectiveness of top-down control of attention in left visual field; α_{right} : effectiveness of top-down control of attention in right-visual field. Standard errors for the estimates are given in parentheses (as estimated by 200 bootstrap repetitions).

the α estimates was larger, but it still seems that the values were accurate to one figure (e.g. GL's true α value in the left side was probably around $0.3 \pm \sim 0.1$).

In the control group, the mean A_{lat} value was 0.50, with minimal variability (S.D. = 0.03), indicating highly symmetrical sensory effects in the left- and right-visual fields. The A_{lat} value of GL (0.26) was lower than the value for any of the eight controls ($P < 0.01$ by a one-tailed binomial test), deviating as much as 8S.D. from the control group mean. Thus, GL had a highly significant difference in the sensory effects between the two sides. The mean A_{ver} value in the control group was 0.57, again with little variability (S.D. = 0.05). Thus, it seems that sensory effects were a little stronger for stimuli in the upper visual field. GL's A_{ver} value of 0.53 was within the normal range.

In the control group, the mean w_{lat} value was 0.52, again indicating symmetric performance in left- and right-visual fields. Unlike the results found for the sensory effects, there was substantial variability between participants (S.D. = 0.11). Still, the w_{lat} value of 0.31 for GL deviated 1.9S.D. from the mean of the control group, more than for any other participant ($P < 0.01$ by a one-tailed binomial test). We conclude that GL's pattern of lateral attentional weighting was abnormal. Concerning vertical attentional weighting, the mean w_{ver} index in the control group was 0.70 (S.D. = 0.15). GL's w_{ver} value was 0.82, within normal variability. Considering A_{ver} and w_{ver} together, it seems that the relatively good performance in the upper visual field was due to both differences in sensory effect and differential attentional weighting. This result held for both GL and the controls.

With multiple elements in the visual field, perception is determined by a combination of sensory effects and attentional weighting (cf. Eq. (3)). GL's A and w values were both substantially reduced in the left side. Thus, under conditions of bilateral stimulation, left-sided stimuli were at a double disadvantage for GL. Since the A_{lat} and w_{lat} indices were about the same (around 0.3), it seems that GL's poor

performance in the left side could be attributed equally to these two factors.

The final parameter of interest in the partial report experiment was α . As in other investigations [49], α values varied considerably in the control group (S.D. = 0.17 and 0.22 in left and right sides, respectively). In the left side, the mean α value in the control group was 0.24, and in the right side, the mean value was 0.12. GL's α values of 0.32 and 0.22 did not deviate significantly from this. Thus, GL's capacity to exert top-down control of attentional selection seemed generally preserved, at least for color as the target-defining variable. This finding was remarkable, since the color report experiment (see below) showed that GL's explicit color perception was much better in the right side.

4.2.2. Color report

In color report, only one stimulus was shown in each trial. Accordingly, only sensory effects (of color) were investigated, whereas attentional weighting should be irrelevant. The sensory effects (accumulated during the effective exposure duration) were estimated separately in the four visual quadrants. As in partial report, vertical comparisons showed slightly better performance with upper-field stimuli for most participants, including GL. However, left-right comparisons were more revealing. Table 4 shows the vertically pooled $A_{\text{left}}(\text{col})$ and $A_{\text{right}}(\text{col})$ values for each participant. A laterality index defined by $A_{\text{lat}}(\text{col}) = A_{\text{left}}(\text{col})/[A_{\text{left}}(\text{col}) + A_{\text{right}}(\text{col})]$ is also shown.

The mean $A_{\text{lat}}(\text{col})$ value in the control group was 0.55, with little variation (S.D. = 0.05). GL's value of 0.16 deviated 8S.D. from the mean, indicating a markedly lower sensory effect for color in the left side. GL's value was farther away from the mean of the control group than was the value of any other participant ($P < 0.01$ by a one-tailed binomial test). The pattern was very similar to that of the A estimates in partial report. Thus, at near-threshold exposure durations, GL's ability to categorize single stimuli was strongly reduced in the left visual field for both color and

Table 4
Color report: model parameters

Participant	$A_{\text{left}}(\text{col})$	$A_{\text{right}}(\text{col})$	$A_{\text{lat}}(\text{col})$
Patient			
GL	0.45	2.38	0.16
Controls			
SW	2.01	1.62	0.55
CP	2.44	2.05	0.54
AN	1.27	0.96	0.57
MT	1.04	0.89	0.54
IH	2.02	1.22	0.62
CB	1.27	0.78	0.62
AL	1.04	0.85	0.55
KH	1.02	1.13	0.47

Note— $A_{\text{left}}(\text{col})$: sensory effect of color in left visual field; $A_{\text{right}}(\text{col})$: sensory effect of color in right-visual field; $A_{\text{lat}}(\text{col})$: laterality index of sensory effect of color.

letter identity. In contrast, control subjects had nearly identical single-stimulus perception in both fields.

4.3. Discussion

The partial report experiment provided measurement of several attentional effects. First, the experiment confirmed the near-threshold effect found in whole report. Using 640 trials at very short exposure durations (compared to about 80 trials in whole report), and a different experimental paradigm, GL's deficit in perceiving left-side stimuli near threshold was firmly established. Furthermore, the experiment showed that her deficit in perceiving single stimuli was exacerbated by distracting stimuli in the right visual field. Thus, according to our TVA analysis, there was an attentional as well as a sensory factor behind GL's left-side deficit.

TVA analysis allowed precise quantification of these two factors and showed that, under bilateral stimulation, they contributed about equally to GL's bias for right-side stimuli. Although GL did not have extinction in the traditional sense, this finding bears on the discussion of sensory versus attentional mechanisms in extinction [12,23,56]. A closer look at the A and w values will clarify this point.

4.3.1. Lateral differences near threshold

By Eq. (2), the accumulated sensory effect (A value) of a stimulus is a product of two factors: the sensory effectiveness, s , and the effective exposure duration ($t - t_0$). On the basis of the partial report data, it is impossible to determine whether reduction in one or the other factor caused the low A values in GL's left side. However, the evidence from the whole report experiment points to t_0 . In whole report, GL's C values (which correspond to sums of v values and are proportional to the s values) were nearly the same in both sides, whereas her t_0 values differed. Due to the experimental design, the exact values of t_0 in partial report could not be estimated, but it seems plausible that the perceptual thresholds were comparable to those found in whole report. The same

physical stimuli were used, only were the letters shown in slightly different positions and fewer at a time. Therefore, at exposure durations close to threshold (such as $t = 60$ ms), a strong lateral difference in GL's performance should be expected. For example, assuming the threshold values of 44 and 56 ms from whole report, the effective exposure duration ($t - t_0$) in partial report would be 16 ms in the left side and 4 ms in the right side. This would result in A values that were about four times larger in the right side, close to the actual ratio between GL's A values in partial report. In conclusion, different perceptual thresholds offer a simple explanation for GL's reduced performance with single stimuli to the left.

As for double stimulation, the partial report experiment showed that GL's attentional weighting of left-side stimuli was quite low. Due to variability in the control group, GL's laterality index for attentional weighting did not deviate as strikingly from controls as did her laterality index for sensory effects, but the deviation was still considerable. In fact, under bilateral stimulation, GL's skewed attentional weighting contributed about as much to her bias for right-side stimuli as did asymmetric A values (specifically, asymmetric sensory thresholds) (see [16], p. 472, for further discussion of covariation between sensory and attentional laterality indexes; also see [19,20,58]).

Our TVA analysis of the data was based on the assumption that only the stimulus letters had attentional weights that were greater than zero. Thus, for a target-alone display, the singly presented target should be the only object with a positive attentional weight. An alternative hypothesis is that not only the (one or two) stimulus letters actually shown on a given trial, but objects (actual stimulus letters or blank areas of space on the display screen) at all of the four possible stimulus locations had attentional weights that were greater than zero. In this case, the results for a target-alone display would reflect not only the accumulated sensory effect of the target but also the attentional weighting of the target. [Specifically, the results would reflect the product of (a) the accumulated sensory effect of the target and (b) the relative attentional weight of the target (i.e. w_{target} divided by the sum of w_{target} and the attentional weights of the three areas of blank space where the target might have appeared).] Similarly, for two-target displays, the results would reflect not only the accumulated sensory effects of the targets, but also the ratios between the attentional weights of the targets and the attentional weights of areas of blank space at the unused target locations. As in the original analysis, the probability that a given target is correctly reported should be less when the target is accompanied by another letter than when the target is presented alone (*divided-attention decrement*, provided that the weight of a target exceeds the weight of a blank spaced at an unused target location). However, the divided-attention decrement predicted by the alternative hypothesis is less than the divided-attention decrement predicted by the original analysis. As the fit between GL's data and the predictions by the original analysis was nearly perfect ($r = 0.98$), the data supported the simple assumption that only the stimulus

letters had attentional weights that were greater than zero. Hence, the data also supported the assumption that the results for target-alone displays reflected the accumulated sensory effects of the targets but not attentional weighting.

4.3.2. Extinction

On account of her deficit in perceiving single stimuli in the left side, GL could not be said to have extinction as classically defined (i.e. preserved ability to report an isolated contralesional stimulus, but impaired ability to report the stimulus when accompanied by an ipsilesional stimulus [23]). Classical extinction implies that only attentional weighting between stimuli is affected. However, the notion of preserved single-stimulus perception in extinction patients derives from simple bed-side confrontation tests. These techniques are probably not sensitive to subtle perceptual deficits. For instance, preserved ability to detect the examiner's finger movements in the contralesional visual field [56] does not rule out sensory deficits for weaker stimuli. As shown in the whole and partial report studies of GL, sensory differences between sides are sometimes evident only near threshold. Even sophisticated experimental studies of extinction [12] have used stimuli well above threshold (e.g. letters exposed for 200 or 500 ms). One may therefore question whether extinction patients are really as "clean" in terms of sensory function as often presumed. This notion was also challenged by Marzi et al. [36] and Smania et al. [51]. They found that patients with extinction or neglect had prolonged reaction time for detection of single contralesional stimuli. However, reaction time represents a composite measure of sensory and motor processes, and it is not clear at which point in processing the patients' delay occurred. In this respect our whole and partial report investigations of GL are more specific. The experiments required no speeded responses, only nonspeeded verbal reports. Accordingly, our results should be less affected by the general slowing of reaction that often follows brain damage. Therefore, our investigation seems to point more directly to a sensory deficit.

Extinction, as measured by traditional clinical methods, is known to be relatively common after damage to the right side of the brain, at least in the acute stage. In the most extensive study of such patients to date, Vallar et al. [56] found that 46 out of 159 unselected patients had extinction (29%). Twenty-five of these had visual extinction (16%). However, one could suspect that this represents only the tip of the iceberg. The study of GL points to the possibility that some patients have mild, persisting forms of inattention that can be revealed only by sensitive psychophysical testing. If this is the case, lateralized attention problems after right hemisphere damage could be much more common than previously thought. Such a large prevalence of extinction-like deficits has been predicted by Duncan [15] on general theoretical grounds (the *biased competition* model of attention). Of course, large-scale group studies are needed to test this hypothesis, but it seems that TVA would provide an adequate analytical frame for such a project. Also, the finding

that clear lateralized attention deficits were found only near GL's stimulation threshold may help guide future studies. Attention deficits may appear most clearly under such challenging conditions for the perceptual system (for related studies of extinction-like phenomena in normal observers, see [43–45]).

4.3.3. Vertical bias

GL had a bias towards reporting stimuli from the upper visual field, but this tendency was shared by most control subjects. For both GL and the control subjects, the effect was primarily related to attentional weighting. Single stimuli were perceived a little better in the upper than in the lower visual field, but in case of double stimulation there was a strong tendency to report only the upper stimulus. Thus, it seems that attentional weights were set higher for upper locations, whereas sensory effectiveness was more equally distributed. Several explanations are possible for this effect. It could simply be related to reading habits: in our culture, we read from top to bottom. However, we also read from left to right, but no systematic horizontal bias was found among control subjects (neither in the lower nor the upper visual field).

Instead a neurological explanation can be proposed. Drain and Reuter-Lorenz [13] found that normal subjects tend to bisect vertical lines above the midpoint, and thus to some extent neglect the lower half of the line (see also [48]). Furthermore, Drain and Reuter-Lorenz found that the effect was stronger in variations of the task that involved object recognition. The authors interpreted the results in terms of Previc's [46] theory of vertical attention, which claims that the ventral pathway of the visual system is mainly concerned with attention to the upper visual field, whereas the opposite holds for the dorsal pathway. Drain and Reuter-Lorenz hypothesized that in the normal brain, the upward bias of the ventral pathway is a little stronger than the downward bias of the dorsal pathway. Object recognition tasks, which specifically activate the ventral pathway, strengthen this upward bias. The letter recognition task used in the partial report experiment should therefore produce a significant upward bias in participants (in case of competing stimuli). Also in case of single stimuli, perception should be a little better in the upper visual field. The findings in partial report fitted this prediction nicely. Also, GL's normal performance on the vertical dimension could be explained by the fact that her lesion involved neither dorsal nor ventral visual pathways. Thus, the normal strength relation between the two anatomical systems was preserved.

In GL the normal upward bias combined with a rightward bias, making her perception of stimuli in the lower left quadrant especially poor. Neglect has often been found to be worse below the horizontal meridian [21,31,42,47], which may be explained by similar mechanisms. In parietal neglect patients, who have often suffered damage to the dorsal visual pathway, the upward bias should be even stronger. Several case studies have found such an effect [11,47], but to our knowledge a large-scale comparison of vertical bias

in patients with and without dorsal pathway lesions has not been conducted.

Recent research indicates that vertical biasing of attention may depend on another spatial category: “near” (i.e. within hand’s reach) versus “far” space. Pitzalis et al. [41] found that in a group of neglect patients, there were more line bisection errors in the lower part of space, but only if stimuli were presented in near space. However, the computer screen in the present experiment was about 70 cm from the observer, and stimuli were not clearly located in either near or far space. It is therefore an open question how the near-far distinction bears on GL’s attentional deficits.

4.3.4. Attentional control

The final parameter estimated in the partial report experiment was α . In spite of a lesion located anteriorly in the brain, a type of damage often related to distractibility [39,60], GL’s α values were normal. In other words she was able to focus adequately on targets in the presence of distractors. Top-down control of attention thus appeared to be normal, at least for selection by color. This indicates that the areas lesioned in GL’s brain, the right anterior basal ganglia and the immediately overlying white matter and frontal gyri, are not critical in performing this kind of selection. The finding is in line with recent imaging studies that have investigated top-down control of attention. Hopfinger et al. [24] found that voluntary control of spatial attention was related to activation in the superior frontal gyrus. Weidner et al. [59] reported that the fronto-median cortex was selectively involved in voluntary shifts of attention between visual dimensions (i.e. color or motion). Both of the mentioned anatomical regions were intact in GL.

The selectivity for color-defined targets was preserved even in the left visual field, where GL had major difficulties reporting the colors. This result replicates that of Duncan et al. [16], who found neglect patients to have preserved α values in both sides, despite clearly inferior color perception to the left. Duncan et al. concluded that, whereas color identity in the neglected field was not available for explicit report, the information was still being used implicitly in the weight setting for targets and distractors. The performance of GL provides a second demonstration of this independence between (explicit) color perception and (implicit) attentional weighting by color. It adds to the growing body of evidence that patients with lateralized attention disorders may process information from the impaired visual field despite being unable to perceive the objects consciously [2,35,37].

4.3.5. Frontal neglect

GL’s partial report performance also bears on the understanding of frontal neglect. Since the first demonstration by Heilman and Valenstein [22], it has been known that frontal lesions can produce symptoms that are similar to the neglect syndrome seen after parietal lesions (see [56], for a study of the prevalence of neglect after frontal and basal ganglia lesions). Traditionally frontal neglect has been de-

scribed as a reduced tendency to perform movements into the contralesional field (“motor neglect” [38,23]). However, frontal neglect may also include perceptual deficits. The nature of these perceptual deficits was investigated by Husain and Kennard [26] in a study of a neglect patient with focal frontal damage. Husain and Kennard reported that the severity of neglect varied with the level of distraction in the right-visual field (“distractor-dependent neglect”). This dependency was not found in another neglect patient with a combined fronto-parietal lesion. In this case, neglect seemed equally severe under all conditions. Husain and Kennard therefore suggested that deficits in perceptual processing, specifically top-down control of attention, is an important component of the frontal neglect syndrome. Furthermore, comparing lesions from five patients with frontal neglect, Husain and Kennard [25] found a common focus in the dorsal aspect of the inferior frontal region and the immediately underlying white matter.

The anatomical region located by Husain and Kennard corresponds closely to GL’s lesion. However, as measured by Mesulam cancellation tests (which include many distracting elements) and clinical behavior, GL did not have neglect. This to some extent contradicts the critical importance of the region located by Husain and Kennard. Still, GL did have attentional disturbances that bear on the discussion of frontal neglect and the syndrome’s proposed relation to the inferior frontal lobe. The study of GL confirms that damage to this area (and the underlying basal ganglia nuclei, which are also traditionally related to motor function) may produce attention deficits that are purely perceptual. In both the whole report and partial report experiments, stimuli were perceived within one fixation (exposure durations ≤ 200 ms), and the tasks required only verbal responses. Despite this, clear visual attentional deficits were found in GL on a range of measures. These findings strongly support the importance of the inferior frontal lobe to visual processing and indicate that lesions in this area may cause purely perceptual deficits in attention. However, contrary to Husain and Kennard’s hypothesis of distractor-dependent neglect, GL’s attentional disturbance did not include distractibility for irrelevant elements. Her α values were normal. Instead, GL’s qualitative pattern of performance in the whole and partial report experiments closely resembled the performance of the parietal neglect patients in Duncan et al. [16]. However, clinically her attention problems were less severe and indeed, required special psychophysical tests to be detected. This finding is in line with a second explanation that Husain and Kennard [26] left open for their results: that their patient with frontal neglect differed quantitatively, not qualitatively, from the other patient with a combined fronto-parietal lesion. That is, neglect was simply less severe in the patient with the focal frontal lesion and showed up only on demanding cancellation tests with many distractors. Whereas frontal neglect patients may have unique attentional deficits with respect to motor exploration, their perceptual deficits may be similar to, but milder than those of parietal patients.

5. Conclusion

This study featured a comprehensive investigation of a single patient's visual attention function. The patient, GL, had suffered a hemorrhage in the right basal ganglia and overlying white matter and frontal gyri. These anatomical structures are usually not thought to be critical for visual function, but GL complained of reduced awareness of the left side. Standard clinical tests revealed no clear deficits in visual attention. Instead we demonstrated GL's attentional disorder by way of psychophysical methods and mathematical modeling. In the first of our two experiments, whole report, we measured central parameters of GL's attentional capacity. In the second experiment, partial report, we investigated how this capacity was distributed in the visual field, and how the distribution depended on the selection required by the task. Using the equations of the TVA model [4] as an analytical frame, estimates of GL's storage capacity of VSTM, total rate of visual information uptake, attentional weight setting, and sensory effectiveness for single stimuli were obtained in different parts of the visual field. On most of these measures, GL could be shown to deviate significantly from an age-matched control group. GL's pattern of deficit consisted in a bilateral reduction of attentional capacity (involving both visual short-term memory and rate of encoding) combined with a bias for stimuli in the right-visual field. The bias was analyzed into a component related to attentional weighting and a sensory component that was evident only near the perception threshold. In general, the study indicated that stimulation near threshold may be an effective way of bringing out subtle deficits in perceptual function.

Overall, the study demonstrated how a minor attention disturbance may be analyzed into distinct components and measured reliably. The study used an experimental method that was developed by Duncan et al. [16], but extended the scope of the investigation to a patient with less obvious deficits than visual neglect. Also, the methodology was refined by the introduction of bootstrap analysis, which permitted evaluation of the reliability of the test results. Finally, the study provided new evidence concerning the importance of frontal and basal ganglia structures for visual attention. In particular, the results suggested that the perceptual component of frontal neglect may be qualitatively similar to that found after parietal lesions, but less severe.

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Appendix A. Bootstrap analysis

The bootstrap is a data-based simulation method for statistical inference, pioneered by Efron [17] (see [18] for further developments). One of the main advantages of bootstrap analysis is that it enables estimation of the standard error of any given sample statistic. The statistic can simply be the mean of the sample, but all parameters that can be computed from the sample (such as the more complicated maximum likelihood estimators of the present study) can be subject to bootstrap analysis.

Bootstrapping depends on the notion of a *bootstrap sample*. The bootstrap sample can be conceived as a resampled version of the original observations. The bootstrap sample is constructed by drawing n elements at random, *with replacement*, from an original sample of n observations. This way, a single observation can be represented 0, 1, 2, ..., or up to n times in the bootstrap sample. The statistic of interest is then computed from the bootstrap sample. This procedure is independently repeated a substantial number of times, producing a distribution of bootstrap estimates. With a large sample size such as several hundred observations, statistical research indicates that 200 repetitions is more than sufficient to obtain a good approximation to the distribution [18]. The standard deviation of the bootstrap distribution may be taken as an estimator of the standard error related to the original sample statistic. That is, the bootstrap analysis produces a quantitative estimate of the robustness of the original parameter estimate.

We describe the procedure used for bootstrap analysis of the whole report data; the analysis of the partial report data was similar. There were 480 trials in the whole report experiment (however, as noted previously, GL performed 504). For each participant, the original set of observations was used to construct 200 bootstrap data sets. Thus, each bootstrap data set consisted of 480 "observations" (or, in the case of GL, 504). To each of these data sets, a maximum likelihood fit was made. This way, 200 sets of parameter estimates were obtained (i.e. sets consisting of 1μ value, $2K$ values, $2t_0$ values, and $10v$ values). The standard deviation of each bootstrap parameter estimate was computed as an approximation of the standard error of the original parameter estimate.

References

- [1] Arndt S, Cizadlo T, O'Leary D, Gold S, Andreasen NC. Normalizing counts and cerebral blood flow intensity in functional imaging studies of the human brain. *NeuroImage* 1996;3:175–84.
- [2] Berti A, Allport A, Driver J, Dienes Z, Oxbury J, Oxbury S. Levels of processing for visual stimuli in an "extinguished" field. *Neuropsychologia* 1992;30:403–15.

- [3] Bullmore E, Horwitz B, Honey G, Brammer M, Williams S, Sharma T. How good is good enough in path analysis of fMRI data? *NeuroImage* 2000;11:289–301.
- [4] Bundesen C. A theory of visual attention. *Psychological Review* 1990;97:523–47.
- [5] Bundesen C. Visual selective attention: outlines of a choice model. *Visual Cognition* 1998;5:287–309.
- [6] Bundesen C. A computational theory of visual attention. In: Humphreys GW, Duncan J, Treisman AM, editors. *Attention, space, and action*. Oxford (UK): Oxford University Press; 1999. p. 54–71.
- [7] Bundesen C. A general theory of visual attention. In: Bäckman L, von Hofsten C, editors. *Psychology at the turn of the millennium. Cognitive, biological, and health perspectives*, vol. 1. Hove (UK): Psychology Press; 2002. p. 179–200.
- [8] Bundesen C, Habekost T. Attention. In: Lamberts K, Goldstone R, editors. *Handbook of cognition*. London: Sage Publications; in press.
- [9] Bundesen C, Harms L. Single-letter recognition as a function of exposure duration. *Psychological Research/Psychologische Forschung* 1999;62:275–9.
- [10] Bundesen C, Shibuya H, Larsen A. Visual selection from multielement displays: a model for partial report. In: Posner MI, Marin OSM, editors. *Attention and performance XI*. Hillsdale (NJ): Erlbaum; 1985. p. 631–49.
- [11] Butter CM, Evans J, Kirsch N, Kewman D. Altitudinal neglect following traumatic brain injury: a case report. *Cortex* 1989;25:135–46.
- [12] di Pellegrino G, De Renzi E. An experimental investigation on the nature of extinction. *Neuropsychologia* 1995;33:153–70.
- [13] Drain M, Reuter-Lorenz PA. Vertical orienting control: evidence for attentional bias and “neglect” in the intact brain. *Journal of Experimental Psychology: General* 1996;125:139–58.
- [14] Duncan J. Visual search and visual attention. In: Posner MI, Marin OSM, editors. *Attention and performance XI*. Hillsdale (NJ): Erlbaum; 1985. p. 85–104.
- [15] Duncan J. Converging levels of analysis in the cognitive neuroscience of visual attention. In: Humphreys GW, Duncan J, Treisman AM, editors. *Attention, space, and action*. Oxford (UK): Oxford University Press; 1999. p. 112–30.
- [16] Duncan J, Bundesen C, Olson A, Humphreys G, Chavda S, Shibuya H. Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General* 1999;128:450–78.
- [17] Efron B. Bootstrap methods: another look at the jackknife. *Annals of Statistics* 1979;7:1–26.
- [18] Efron B, Tibshirani RJ. *An introduction to the bootstrap*. London: Chapman & Hall; 1998.
- [19] Gorea A, Sagi D. Failure to handle more than one internal representation in visual detection tasks. *Proceedings of the National Academy of the United States of America* 2000;97:12380–4.
- [20] Gorea A, Sagi D. Natural extinction: a criterion shift phenomenon. *Visual Cognition* 2002;9:913–36.
- [21] Halligan PW, Marshall JC. Is neglect (only) lateral? A quadrant analysis of line cancellation. *Journal of Clinical and Experimental Psychology* 1989;11:793–8.
- [22] Heilman KM, Valenstein E. Frontal lobe neglect in man. *Neurology* 1972;22:660–4.
- [23] Heilman KM, Watson RT, Valenstein E. Neglect and related disorders. In: Heilman KM, Valenstein E, editors. *Clinical neuropsychology*. 3rd ed. Oxford: Oxford University Press; 1993.
- [24] Hopfinger JB, Buonocore MH, Mangun GR. The neural mechanisms of top-down attentional control. *Nature and Neuroscience* 2000;3:284–91.
- [25] Husain M, Kennard C. Visual neglect associated with frontal lobe infarction. *Journal of Neurology* 1996;243:652–7.
- [26] Husain M, Kennard C. Distractor-dependent frontal neglect. *Neuropsychologia* 1997;35:829–41.
- [27] Karnath HO, Ferber S, Himmelbach M. Spatial awareness is a function of the temporal not the posterior parietal lobe. *Nature* 2001;411:950–3.
- [28] Kasten E, Gothe J, Bunzenthall U, Sabel BA. Kampimetrische Untersuchung visueller Funktionen am Computermonitor. *Zeitschrift für Psychologie* 1999;207:97–118.
- [29] Kasten E, Wüst S, Behrens-Baumann W, Sabel BA. Computer-based training for the treatment of partial blindness. *Nature and Medicine* 1998;4:1083–7.
- [30] Kimura D. The asymmetry of the human brain. *Scientific American* 1973;228:70–8.
- [31] Ladavas E, Carletti M, Gori G. Automatic and voluntary orienting of attention in patients with unilateral neglect: horizontal and vertical dimensions. *Neuropsychologia* 1994;32:1195–208.
- [32] Logan GD. An instance theory of attention and memory. *Psychological Review* 2002;109:376–400.
- [33] Logan GD, Gordon RD. Executive control of visual attention in dual-task situations. *Psychological Review* 2001;108:393–434.
- [34] Luck SJ, Vogel EK. The capacity of visual working memory for features and conjunctions. *Nature* 1997;390:279–81.
- [35] Marshall JC, Halligan PW. Blindsight and insight in visuo-spatial neglect. *Nature* 1988;336:766–7.
- [36] Marzi CA, Smania N, Martini MC, Gambina G, Tomelleri G, Palamara A, et al. Implicit redundant-targets effect in visual extinction. *Neuropsychologia* 1996;34:9–22.
- [37] McGlinchey-Berroth R. Visual information processing in hemispatial neglect. *Trends in Cognitive Sciences* 1997;1:91–7.
- [38] Mesulam MM. A cortical network for directed attention and unilateral neglect. *Annals of Neurology* 1981;10:309–25.
- [39] Paus T, Kalina M, Patockova L, Angerova Y, Cerny R, Mecir P, et al. Medial vs. lateral frontal lobe lesions and differential impairment of central-gaze fixation maintenance in man. *Brain* 1991;114:2051–67.
- [40] Peers P, Ludwig C, Rorden C, Cusack R, Driver J, Bundesen C, et al. Using Bundesen’s theory of attention to quantify attentional deficits following unilateral brain injury. *Abstracts of the Cognitive Neuroscience Society* 2002;9:19.
- [41] Pitzalis S, Di Russo F, Spinelli D, Zoccolotti P. Influence of the radial and vertical dimensions on lateral neglect. *Experimental Brain Research* 2001;136:281–94.
- [42] Pitzalis S, Spinelli D, Zoccolotti P. Vertical neglect: behavioral and electrophysiological data. *Cortex* 1997;33:679–88.
- [43] Pollmann S. A pop-out induced extinction-like phenomenon in neurologically intact subjects. *Neuropsychologia* 1996;34:413–25.
- [44] Pollmann S. Extinction-like effects in normals: independence of localization and response selection. *Brain and Cognition* 2000;44:324–41.
- [45] Pollmann S, Zaidel E. The role of the corpus callosum in visual orienting: importance of interhemispheric visual transfer. *Neuropsychologia* 1998;36:763–74.
- [46] Previc FH. Functional specialization in the lower and upper visual field in humans: its ecological origins and neurophysiological implications. *Behavioral and Brain Sciences* 1990;13:519–75.
- [47] Rapczak SZ, Cimino CR, Heilman KM. Altitudinal neglect. *Neurology* 1988;38:277–81.
- [48] Shelton PA, Bowers D, Heilman KM. Peripersonal and vertical neglect. *Brain* 1990;113:191–205.
- [49] Shibuya H. Efficiency of visual selection in duplex and conjunction conditions in partial report. *Perception and Psychophysics* 1993;54:716–32.
- [50] Shibuya H, Bundesen C. Visual selection from multielement displays: measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance* 1988;14:591–600.
- [51] Smania N, Martini MC, Gambina G, Tomelleri G, Palamara A, Natale E, et al. The spatial distribution of visual attention in hemineglect and extinction patients. *Brain* 1998;121:1759–70.
- [52] Sperling G. The information available in brief visual presentations. *Psychological Monographs* 1960;74:11. Whole No. 498.

- [53] Sperling G. A model for visual memory tasks. *Human Factors* 1963;5:19–31.
- [54] Sperling G. Successive approximations to a model for short term memory. *Acta Psychologica* 1967;27:285–92.
- [55] Vallar G, Perani D. The anatomy of unilateral neglect after right-hemisphere stroke lesions. A clinical/CT-scan correlation study in man. *Neuropsychologia* 1986;24:609–22.
- [56] Vallar G, Rusconi ML, Bignamini L, Germiniani G, Perani D. Anatomical correlates of visual and tactile extinction in humans: a clinical CT scan study. *Journal of Neurology, Neurosurgery, and Psychiatry* 1994;57:464–70.
- [57] Vogel EK, Woodman GF, Luck SJ. Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance* 2001;27:92–114.
- [58] Walker R, Findlay J, Young AW, Welch J. Disentangling neglect and hemianopia. *Neuropsychologia* 1991;29:1019–27.
- [59] Weidner R, Pollmann S, Müller HJ, von Cramon DY. Top-down controlled visual dimension weighting: an event-related fMRI study. *Cerebral Cortex* 2002;12:318–28.
- [60] Woods DL, Knight RT. Electrophysiologic evidence of increased distractibility after dorsolateral prefrontal lesions. *Neurology* 1986;36:212–6.