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ATTENTIONAL FUNCTIONS IN DORSAL AND VENTRAL SIMULTANAGNOSIA

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Whole report of brief letter arrays is used to analyse basic attentional deficits in dorsal and ventral variants of simultanagnosia. Using Bundesen's Theory of Visual Attention (TVA), a number of previous theoretical suggestions are formalised and tested, including primary deficit in processing more than one display element, attentional stickiness, foveal bias, and global weakness of the visual representation. Interestingly, data from two cases, one dorsal and one ventral, show little true deficit in simultaneous perception, or selective deficit in those TVA parameters (short-term memory capacity, attentional weighting) specifically associated with multi-element displays. Instead there is a general reduction in speed of visual processing (processing rate in TVA), effective even for a single display element but compounded when two or more elements compete.

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INTRODUCTION

Simultanagnosia and its variants

Impairments in seeing several things at once—the different objects of a cluttered visual scene, components of a picture, or letters of a word—define the clinical term "simultanagnosia." Often, such impairments have been interpreted as an attentional restriction—an exaggeration of normal limits on the ability to identify several different things at once. In this paper, we use a theory of normal attentional functions—Bundesen's (1990) Theory of Visual Attention, or TVA—to analyse impairments in simultanagnosia.

In the literature, the general term simultanagnosia has been used to describe two somewhat different types of patient (Farah, 1990). In "dorsal simultanagnosia" or Bálint's syndrome (see Bálint, 1909/1995; Friedman-Hill, Robertson, & Treisman, 1995; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994; Luria, 1959), there are generally bilateral parietal or occipito-parietal lesions. In addition to impairments in visually guided reaching, stimulus localisation and eye movement control, patients experience severe restriction in visual awareness. Bálint's patient, for example, would often identify only one of two intersecting shapes drawn on a blackboard, remaining unaware of the other's presence until prompted, while Luria's patient explained that he could not mark the centre of a cross because, as his pencil approached the page and entered awareness, the cross itself disappeared from view. In "ventral simultanagnosia" (see Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978), there is usually a single left occipital lesion. In this case, complaints of restricted awareness are less dramatic, but include an inability to "make sense of" a picture because only parts are noticed and, conspicuously, a tendency to read words letter by letter (hence the term "pure alexia" also used to describe patients of this sort). The bulk of this paper presents a detailed analysis of a single dorsal simultanagnosic patient, GK (Humphreys et al., 1994). For comparison, less complete data are presented for a ventral patient, MP.

Experimental investigations of simultanagnosia have typically compared identification of singly and multiply presented letters, forms, or drawings (e.g., Coslett & Saffran, 1991; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978). Though some deficit is often apparent for even one stimulus presented alone, apparently greater difficulties are seen when several stimuli must be identified at once. The patients of Kinsbourne and Warrington, for example, sometimes failed to identify both letters of a pair even when these were shown for 1000 ms or more. As we shall see, TVA allows us to distinguish and evaluate a variety of alternative "attentional" explanations for results of this sort. Indeed, it provides an integrated framework within which several theoretical approaches to the problem of simultanagnosia can be formalised, related, and tested.

Theory of Visual Attention (TVA)

In contrast to many serial models of attention (e.g., Treisman & Gelade, 1980), TVA is based on parallel, competitive processing (Rumelhart, 1970). Objects or elements in the visual field compete for access to a visual short-term memory (VSTM). Their competitive strength or weight is determined in part by task context, allowing preferential processing of relevant or target elements. In previous work, the empirical motivation for the various components of TVA has been considered in detail, and the theory fit to data from a wide variety of attentional paradigms including partial and whole report, visual search, redundant target detection, and cued reaction time (Bundesen, 1990, 1998). In this section we give an outline of the theory and the component functions it distinguishes.

Much of the theory can be understood in the context of a simple divided attention task, *whole report* (Sperling, 1960). In whole report, the participant is shown a brief array of letters, shapes, or other elements. Commonly, the array is followed by a backward mask intended to interrupt processing. The task is simply to identify and report as many array elements as possible. Performance is measured as a function of the number of elements in the array and the stimulus onset asynchrony (SOA) between array and mask.

Exponential processing times

Consider first the simple case of a display consisting of a single element *i*. According to TVA, this element can be identified when an appropriate categorisation is entered into VSTM. A basic assumption of the theory is exponentially distributed processing time: The probability of identification P_i as a function of time t is described by the equation

$$P_i = 1 - \frac{1}{e^{v_i(t-t_0)}} \quad (1)$$

Example functions are shown in Figure 1; similar real data are provided by Bundesen (1998). Equation 1 has two parameters. The first, t_0, represents a minimum exposure duration required before processing can begin. In Figure 1 it has a typical value of 20 ms. Although t_0 is important in fitting real data, its interpretation is of no concern here. Instead we are concerned with the rate parameter v_i, determining how quickly performance increases once processing has begun. Numerically, v_i is the slope of the identification function at t_0. Functions for three values of v_i are illustrated in Figure 1. For a single-element display, v_i may be taken as a measure of sensory efficiency, determined by such factors as stimulus discriminability, retinal eccentricity, etc.

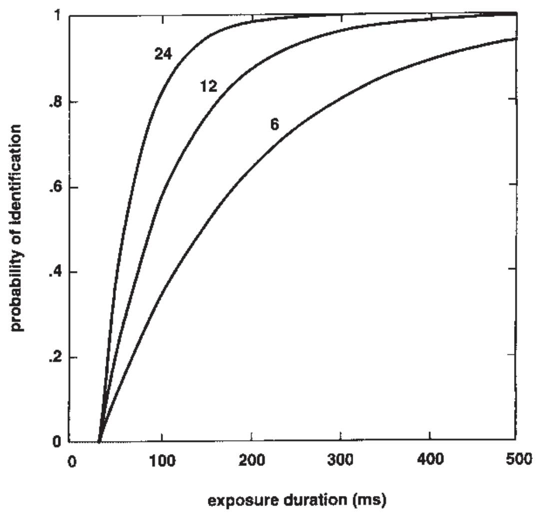


Figure 1. *Example identification functions for three different processing rates (v_i = 6, 12, 24 elements/s).*

Competitive modulation of rate

In TVA, competitive processing is implemented through modulation of rate parameters (v values) in multi-element displays. Specifically, each element *i* in a display of *n* elements is given an *attentional weight*, w_i. Its processing rate is then determined by the equation

$$v_i = s_i \frac{w_i}{\sum_{j=1}^{n} w_j} \quad (2)$$

In this equation, s_i is the v value for element *i* presented alone. It thus represents basic sensory efficiency for that element. The weight ratio $w_i/\Sigma w_j$ measures how strongly processing rate is reduced by competition from other elements in the display. For a display consisting of *n* equally weighted elements, for example, v values for each element are their single-element values multiplied by $1/n$. By way of illustration, Figure 1 shows the consequences of multiplying a basic v value of 24 elements/*s* by 1/2 (array of 2 equally weighted elements) or 1/4 (array of 4 equally weighted elements). As the number of array elements is increased, the rate of processing any given element (and hence the probability that it will be identified at any given exposure) goes down.

For a multi-element display, v values for each element can be estimated (see later) from functions relating the probability of identifying that element to exposure duration. A useful measure of overall processing rate is then capacity *C*, defined as the sum of v values for all display elements. This definition of capacity brings an interesting property: If basic sensory efficiency s_i is approximately constant across elements, then it follows that *C* will also be approximately constant across variations in both the number of elements and their attentional weighting. Since weight ratios $w_i/\Sigma w_j$ for the elements of a display always sum to 1, it follows from Equation 2 that v values for these elements will always sum to s_i. In this sense C—measured by summing empirical v values for the different elements in a display—may be taken as a basic processing capacity that can be arbitrarily divided by variations in attentional weighting.

A further understanding of C can be obtained by considering another standard score in whole report; the mean total number of elements reported for each exposure duration t. As we have seen, v_i for each element i is the slope of the function relating P_i to t at t_0. As the sum of these v values, C accordingly may be visualised as the corresponding slope of the function relating the mean total number of items reported to t at t_0 (see Figure 3). Independent of variations in the number of display elements or attentional weighting, higher values of C mean faster processing, and a steeper initial increase in number of elements reported per unit time.

VSTM capacity (K)
One further limitation is needed to understand whole report performance with displays of more than four or five elements. As exposure duration increases, the number of elements reported reaches an asymptote in the region of three to four (Coltheart, 1972; Sperling, 1967). Following Sperling, TVA interprets this asymptote as the capacity of VSTM, denoted K. Thus only the first K elements to complete processing can be stored in VSTM and made available for report.

In this sense processing in TVA can be understood as a *race* between display elements. Processing speeds for each element are set by Equations 1 and 2. The first K elements to complete processing are available for report; subjectively they are "attended" and reach awareness. Remaining elements are subjectively "unattended" and lost.

Depending on array size, accordingly, two separate factors contribute to conventional "divided attention decrement," or loss of performance as the number of attended objects increases (Broadbent, 1958; Treisman, 1969). For all array sizes, reduced v values associated with increasing n mean slower processing for each element, and reduced chance of correct identification before a display terminates (Equation 2). For array sizes above K, in addition, further elements cannot be stored once VSTM is filled. As considered in detail by Bundesen (1990), Equations 1 and 2, augmented by a limited VSTM capacity K, allow TVA to produce excellent fits to whole report data gathered across wide variations in number of array elements n and exposure duration t. These fits concern not simply the mean number of elements reported, but the whole distribution of frequencies of report of 0, 1, . . ., n elements for all n and t combinations.

Attentional weighting
Above we considered the case of equal attentional weighting in a multi-element display. The point of attentional weighting, however, is to give some elements priority over others. Returning to Equation 2, an element with high weight is processed relatively well (numerator of weight ratio large), and interferes strongly with processing of other elements (large contribution to denominator of all weight ratios). An element with low weight is processed poorly (numerator of weight ratio small), and interferes little with processing of other elements (little contribution to denominator of weight ratios).

In TVA, any form of attentional priority can be implemented by differential attentional weighting. In general, weight setting is the mechanism for *top-down control*, or attentional priority for inputs of relevance to current behaviour. For present purposes, the most important aspect of attentional weighting will be priority for one region of space, implemented by giving elements in the favoured region increased weights relative to elements elsewhere.

Attentional functions in simultanagnosia

The attraction of TVA lies in its potential to distinguish and relate a number of separate components of attentional function. In principle, this should take us far beyond the simple idea that some visual disorder involves "impaired attention." The approach is illustrated by a recent analysis of whole report and related deficits in patients with right parietal lobe lesions and variable degrees of left neglect (Duncan, Bundesen, Olson, Humphreys, Chavda, & Shibuya, 1999). In addition to the expected rightward attentional bias (higher weights for right field elements), we found major, bilateral reductions in *C* and modest reductions in *K*. In contrast to these impairments, there was a striking bilateral preservation of top-down control, or attentional priority, for targets when arrays contained a mixture of targets to be reported and nontargets to be ignored. The results show that the perceptual impairments of left neglect patients derive not just from rightward bias, but from substantial bilateral reductions in the total rate of information uptake. They show also that not all aspects of attentional function are impaired in the contralesional field.

As regards simultanagnosia, it seems possible that each of the major components of TVA could in principle contribute to difficulties in processing simultaneous inputs. At the same time, deficits in each component should be associated with their own, characteristic data pattern. In this section, we outline possible deficits according to TVA and relate them to previous findings.

VSTM capacity (K)

Taken at face value, simultanagnosia suggests a primary deficit in processing any additional element in a visual display after the first. Such a deficit is implied, for example, by the proposal that perception could be "sticky," or hard to move from one focus to another (see, e.g., Kinsbourne & Warrington, 1962). In TVA, the most straightforward way to implement such a deficit is reduction in *K*. A *K* value of 1, for example, would leave processing of a single display element normal, but render report of two or more elements impossible.[1]

For variants of whole report, reductions in *K* should affect the asymptote rather than the initial slope of the function relating mean number of elements reported to exposure duration. For the case of $K = 1$, performance should increase steeply until one item is reported on every trial, but remain constant at this value over substantial further increases in exposure. Given normal attentional weighting, the position from which the single reported element is drawn should vary somewhat randomly across trials.

Perhaps the closest approximation to this data pattern was described for a single patient by Coslett and Saffran (1991). In this patient there were bilateral occipitotemporal lesions, with extension into the inferior parietal lobule on the right. Displays of a single picture were identified at an exposure (40 ms, unmasked) comparable to that required by normal controls. When two pictures were shown simultaneously, however, the patient always reported one, but rarely two, until exposures rose to 1 s or more. The single reported object came randomly from all four display positions employed (above, below, and to left or right of fixation). For this patient, the results indeed suggest primary reduction in *K* and hence pure deficit in processing any display elements beyond the first.

Processing rate (C)

Reductions in *C* imply that all visual processing—even the processing of single elements—should be slowed. In fact, several previous interpretations of simultanagnosia have this character. Luria (1959), for example, proposed a general weakening of visual traces in Bálint's syndrome, accompanied by mutual inhibition such that all but the strongest competitors were lost. Bálint (1909/1995) similarly proposed a general weakening of visual representations, affecting even single objects but most severe when two or more were present at once.

For variants of whole report, reductions in *C* imply reduced initial slope in the function relating number of elements reported to exposure. Importantly, this deficit should be similar across variations in the number of display elements, extending even to displays of a single object.

Perhaps surprisingly, few studies of simultanagnosic deficits have involved serious investigation of single-element processing; emphasis has instead

[1] TVA does not deal in detail with report of elements from VSTM, and how this frees the store for further inputs. The assumption is, however, that very substantial exposure durations—above the range of most experiments—will be needed before more than *K* elements can be reported from any one display.

gone to the conspicuous difficulty with multi-element arrays. At the same time, it is clear from several reports that single-element processing can certainly be abnormal in both ventral (Kinsbourne & Warrington, 1962) and dorsal (Bálint, 1909/1995) simultanagnosics. Without a detailed, quantitative comparison, it is hard to establish whether observed deficits for multi-element arrays are in fact out of line with single-element performance. From previous data, accordingly, it is hard to determine the contribution of C to simultanagnosic deficits; and in this sense, indeed, whether the term "simultanagnosia" is always apt for these patients.

Attentional weighting: Positional bias

Particular difficulty with multi-element displays can also be a reflection of disordered attentional weighting. As an extreme case, consider two display locations, for one of which the attentional weight is very much higher than the other. Elements in either location will be processed normally when they are presented alone. In the absence of attentional competitors, attentional weights are of no significance (Equation 2). When elements are present in both locations, however, only the element in the preferred location will be easily identified. In the extreme case, the weight ratio may be so large as to reduce the v value for the nonpreferred location towards zero.

Assessing this possibility requires separate scoring of display elements in each possible position. For a multi-element (but not a single-element) display, the prediction is that v values should be unusually high in some positions but unusually low or close to zero in others.

Two versions of this hypothesis may be relevant to simultanagnosia. The first is simple unilateral extinction, or deficit in processing inputs from one side of space in the presence of simultaneous, competing inputs on the other. Since elements on either side are processed well when they occur alone, such a deficit strongly implies unequal attentional weights on the two sides (see Duncan et al., 1999). Ventral simultanagnosics—with their characteristic left occipital lesion—have indeed been reported to favour left field items (Kinsbourne & Warrington, 1962; Rapp & Caramazza, 1991), in line with the more general finding that contralesional extinction is extremely widespread following many different kinds of unilateral brain damage (Bender, 1952; Vallar, Rusconi, Bignamini, Geminiani, & Perani, 1994). Despite their bilateral lesions, lateral biases can also be seen in dorsal simultanagnosics, Bálint's (1909/1995) patient, for example, showing a clear preference for the right.

For dorsal simultanagnosia, a strong preference is also often noted for objects at the fovea (Bálint, 1909/1995; Hécaen & De Ajuriaguerra, 1954). Indeed, this is what Bálint meant by his term "psychic paralysis of gaze"-a capture by the object at the fovea so strong that it could not easily be broken. Others, too, have seen Bálint's syndrome as a form of bilateral extinction of objects in both peripheral visual fields (e.g., Harvey & Milner, 1995). Such ideas imply strongly imbalanced attentional weight for foveal and peripheral inputs.

Summary

Evidently, TVA suggests a range of separate basic deficits that could underlie or contribute to simultanagnosia. Each, furthermore, finds some support in the literature, implying that simultanagnosia may often not be a unitary deficit, or that its cause may be different in different variants.

TVA also defines characteristic data patterns for each possible basic deficit. In the experiments that follow, we use several versions of whole report, comparison of single- and multi-element displays, and separate scoring of display positions to distinguish deficits in VSTM capacity K, processing rate C, and spatial attentional bias.

DORSAL SIMULTANAGNOSIA

The patient

GK, a former businessman, suffered two strokes at the age of 46. The resulting lesions, reconstructed from an MRI scan taken 9 years post-stroke, are

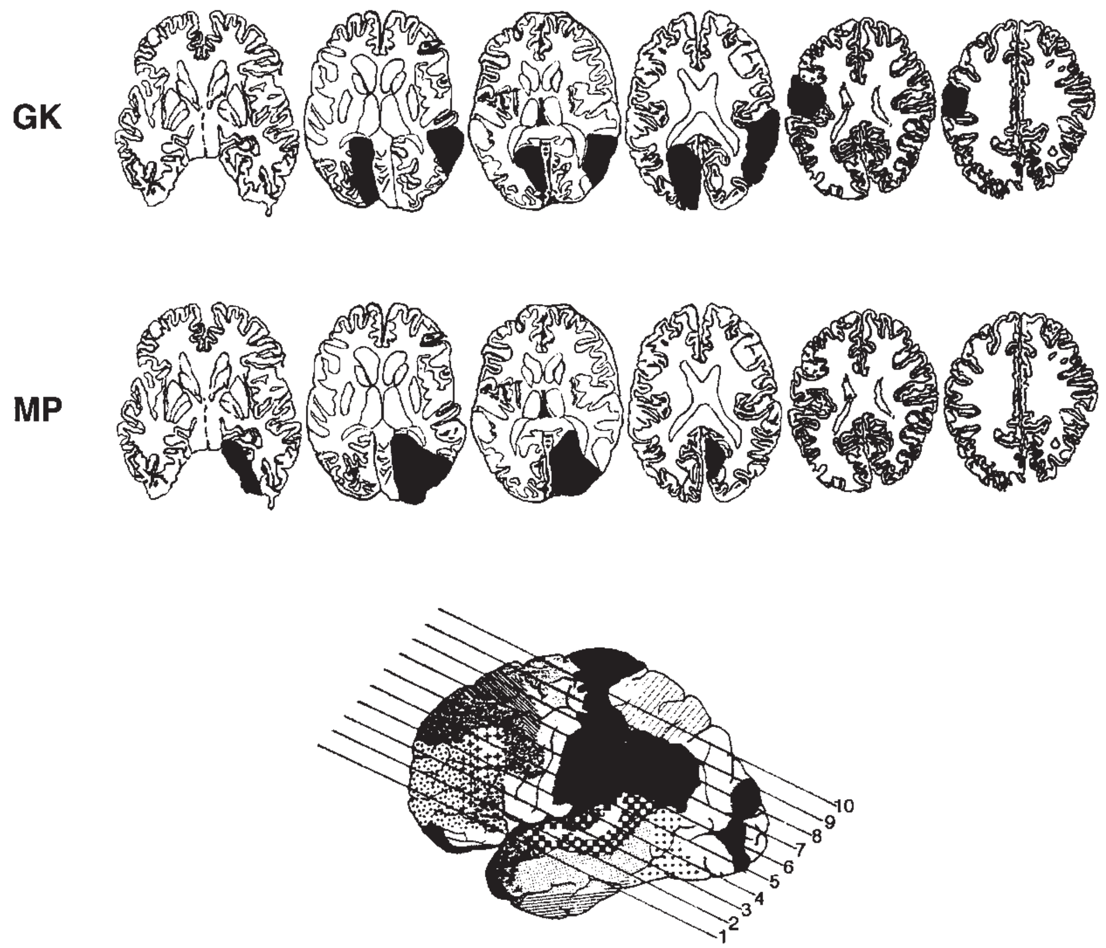


Figure 2. *Lesions for dorsal (GK) and ventral (MP) patients, traced onto standard slices from Gado, Hanaway, and Frank (1979). The 10 slices from Gado et al. are illustrated at bottom; only slices 3–8 are used here. The left of each slice represents the right hemisphere. Slice templates from "Functional Anatomy of the Cerebral Cortex by Computed Tomography," by M. Gado, J. Hanaway, and R. Frank, 1979,* Journal of Computer Assisted Tomography, 3, *1–19. Copyright 1979 by Lippincott, Williams & Wilkins. Adapted with permission.*

shown in radiological convention (left–right reversed) in Figure 2. Like other cases (Bálint, 1909/1995; Friedman-Hill et al., 1995), GK's damage is complex but with bilateral involvement of the inferior parietal lobule. In the right hemisphere there are two lesions, one in the peri-Sylvian region, affecting primary sensorimotor cortex and parts of the inferior parietal lobule, and the other affecting a large region of the medial occipital lobe, including parts of striate and extrastriate cortex. In the left hemisphere there is a single lesion, predominantly parietotemporal but extending back towards the occipitotemporal junction.

GK has the classical symptoms of Bálint's syndrome. He has a severe simultanagnosia, commonly reporting only one of two objects in a display even with an exposure of up to 2 s (Humphreys et al., 1994). His descriptions of complex pictures make reference to only a few of the objects present, so that he is often unable to grasp the meaning of the scene as a whole. He has optic ataxia, showing misreaching to objects under visual guidance; reaching under proprioceptive guidance is somewhat better. Visual perception of spatial location is also very impaired when assessed by verbal report. As in Bálint's (1909/1995) patient, there is a tendency to left-sided extinction under bilateral stimulus presentation (Gilchrist, Humphreys, & Riddoch, 1996). Despite intact visual fields, measured with Goldman perimetry, GK is registered as functionally blind and walks with a cane.

The present experiments were carried out 7 (Experiments 1 and 4), 9 (Experiment 2), and 12 (Experiment 3) years post-stroke. GK's general symptoms appeared to be stable over this period.

Experiment 1

In Experiment 1 we focused on the capacity parameters *K* (VSTM capacity) and *C* (processing rate). The task was whole report. To minimise any impact of lateral attentional bias, stimulus displays were vertical columns of five letters presented in either the left or right visual field. For each participant (GK and a group of seven age-matched controls), data were collected at three exposure durations, each used both with and without backward masks, aiming for a broad spread of performance. Following each display, participants were asked to report just the identities (not locations) of as many letters as they could.

For each participant, fits to TVA were obtained by estimating a total of 13 parameters. The detailed fitting procedure has been described elsewhere (Duncan et al., 1999); in brief, for any combination of parameters, the theory can be used to calculate the probability of the exact report observed on each trial, and best fitting parameters were chosen as those for which, across trials, the joint probability of all observed reports was maximal.

First there are two parameters concerned with effective processing times for each display. The first of these, t_0, was defined earlier as the minimum exposure duration required before processing can begin. The second, μ, is an estimated additional duration available when displays are unmasked; a detailed justification for this treatment of unmasked displays is provided by Bundesen (1990). For a true exposure duration of t, effective exposure duration was thus calculated as $t - t_0$ for masked displays, and $t - t_0 + \mu$ for unmasked displays. For each participant, data were thus available for six effective exposure durations, for both left- and right-field arrays. Though important in data fitting, parameters t_0 and μ are of no immediate theoretical interest here. In the data-fitting procedure, they were constrained to be the same for arrays on either side.

Second, there are 10 v values, one estimated for each possible letter position (five vertical positions in each hemifield.) As processing rate parameters, v values reflect how quickly performance improves as a function of effective exposure duration, separately for letters in each display position. Theoretically (see Equation 2), v values are jointly determined by sensory efficiency and attentional weighting. As we have described, total processing rate or capacity C for any array is defined as the sum of v values for all elements in that array. By summing the estimated v values we thus obtained separate values of C for left (C_L) and right (C_R) field arrays.

The final parameter is *K*, the capacity of VSTM. In line with our previous findings for both neglect patients and controls (Duncan et al., 1999), *K* was constrained to be the same for the two hemifields. As we have seen, *K* represents the upper limit on each participant's whole report performance. According to TVA, it should correspond both to the asymptote of the function relating mean number of letters reported to exposure duration, and to the maximum number of letters reported on a single trial. In practice, the second of these is especially significant in fitting trial-by-trial data; typically, the data show the same maximum number of letters reported across a range of different exposure durations, and this number strongly determines the best-fitting estimate of *K*. Noninteger values of *K* are treated as probability mixtures; for example, a value of 3.7 is treated as a mixture of trials in which $K = 3$ with probability 0.3 and $K = 4$ with probability 0.7. The result in practice is that *K*, rounded up to the nearest integer, corresponds to the maximum number of letters ever reported on a single trial.

Method

Participants. In addition to GK, data were gathered for seven healthy controls, four women and three men, aged between 52 and 80 years (mean 68).

Task and procedure. The experiment was controlled by an IBM-PC compatible computer running custom software. Stimuli were presented on a standard monitor with black background. As no chin rest was used for precise control of viewing distance, reported visual angles are approximate.

The initial part of each trial was an unscored task designed to encourage central fixation. The trial began with a central white fixation dot. When the experimenter pressed a key, this dot was replaced for 300 ms by a central white digit, 0.3° in height, which the participant immediately read aloud. In some sessions with GK, the experimenter watched the patient's eyes to ensure that no detectable movements occurred between this central task and the subsequent display. In fact, GK had no difficulty maintaining fixation; no trials were excluded because of detected eye movements.

The fixation point reappeared while the digit response was given; following this, a second keypress from the experimenter initiated the main stimulus display. When the key was pressed, the fixation point disappeared immediately, and the display itself appeared 100 ms later. It was a column of five letters, centred on the horizontal meridian, 2.4° to left or right of fixation. The height of each letter was 0.5°; the whole column measured 6.4° with letters equally spaced. Letters were drawn from the set ABEFHJKLMNPRSTWXYZ; in different trial blocks, they were either all red or all green. After a predetermined exposure duration, the display was immediately replaced by either a blank screen (unmasked exposures) or a 500 ms mask. The mask consisted of separate characters in each possible display location (i.e., two columns of five characters to left and right). Each mask character was a white square, 0.75° in height, with a horizontal line connecting the midpoints of left and right sides, a vertical line connecting midpoints of top and bottom sides, and diagonal lines connecting opposite corners. The task was simply to name as many letters as possible, in any order. Only identities, not locations, were reported. Responses were unspeeded, and typed into the computer by the experimenter as they were given. Participants were asked to report only letters they were fairly sure they had seen.

Exposure durations were set in an initial practice session, aiming for a broad spread of performance. Three exposures were chosen for each participant (Table 1), each used both with and without masks. For each participant there were accordingly 12 trial types (2 sides × 3 exposures × 2 mask conditions), presented equally often and in random order in each block.

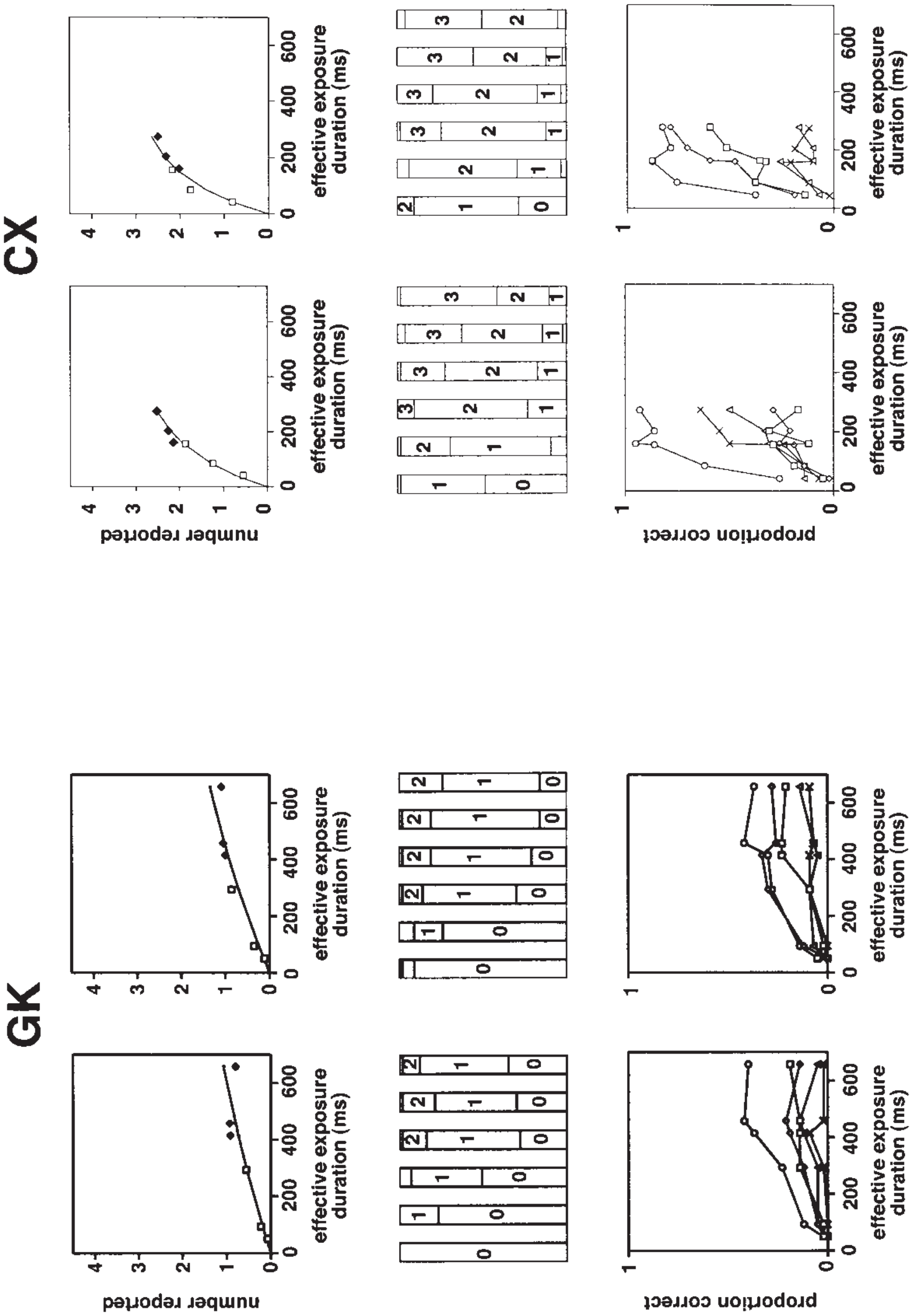
Each participant was tested over a number of sessions on different days. The number of trials completed on any given day varied widely. In total, GK completed 516 scored trials, while the number for controls ranged from 504 to 535.

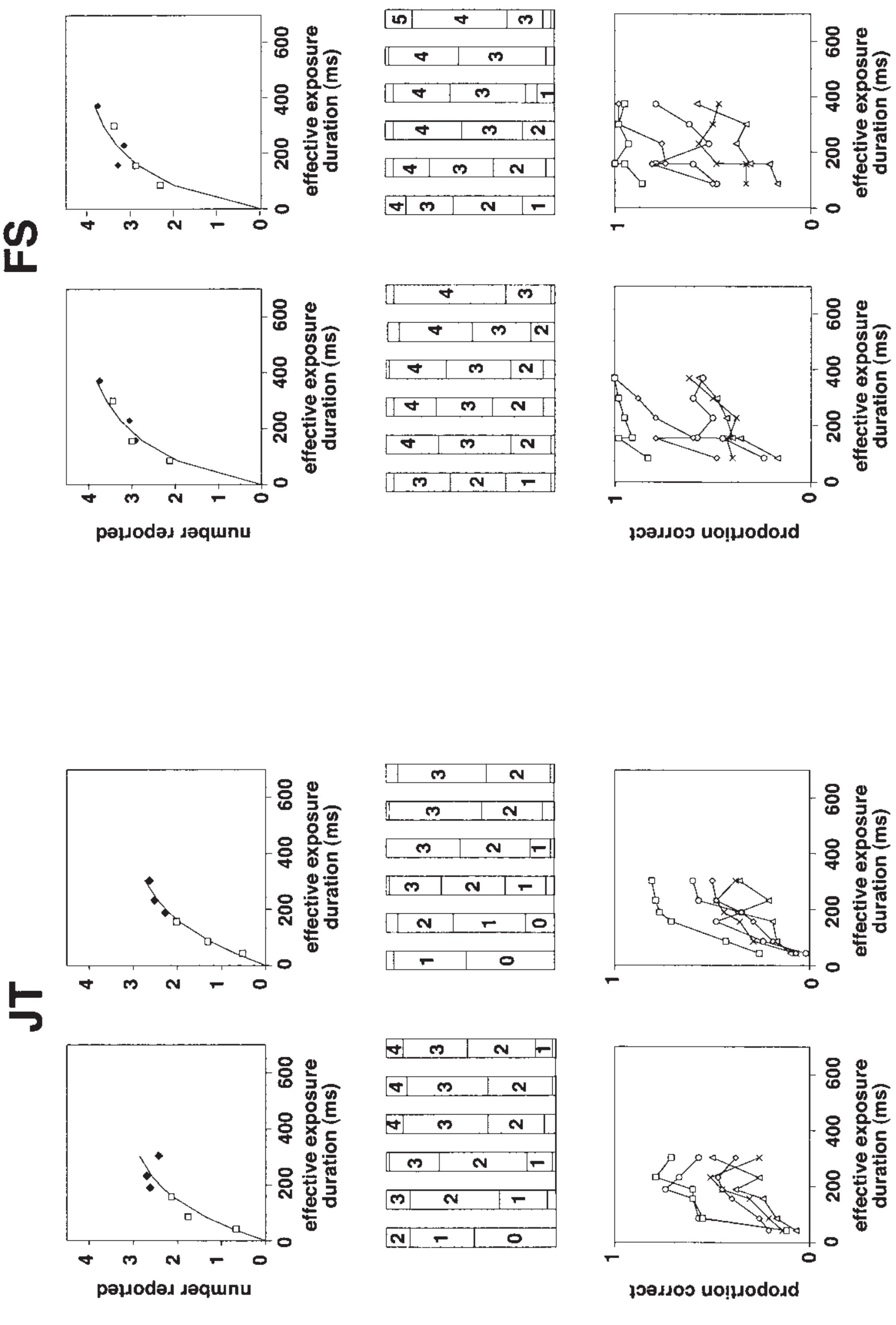
Results

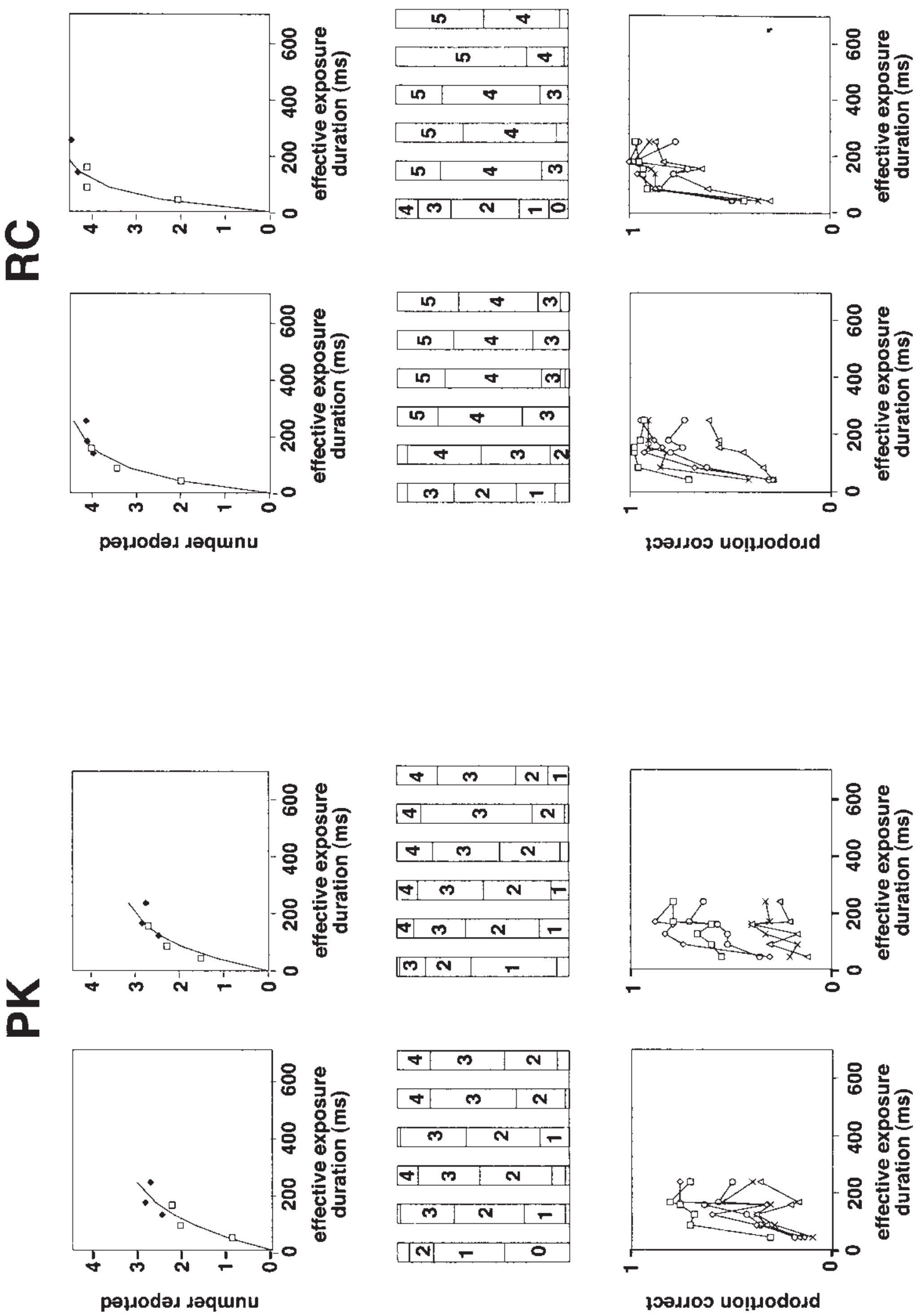
Results for all participants appear in Figure 3 over the next four pages. For each participant, data are shown separately for displays in left (left panels) and right (right panels) visual fields. Upper panels show mean number of letters correctly reported on each trial as a function of effective exposure duration. Data are shown separately for masked (open squares) and unmasked (filled diamonds) displays, with effective exposure durations calculated as described above. Solid lines show fits from TVA. Middle panels show proportions of trials with

Table 1. *Experiment 1: Exposure durations*

Participant	*Exposure durations (ms)*		
Patient			
GK	157,	200,	400
Controls			
CX	43,	86,	157
JT	43,	86,	157
FS	86,	157,	300
PK	43,	86,	157
RC	43,	86,	157
RK	43,	86,	157
RP	43,	86,	157


GK
CX
number reported
effective exposure duration (ms)
proportion correct


FS
JT
number reported
proportion correct
effective exposure duration (ms)


PK
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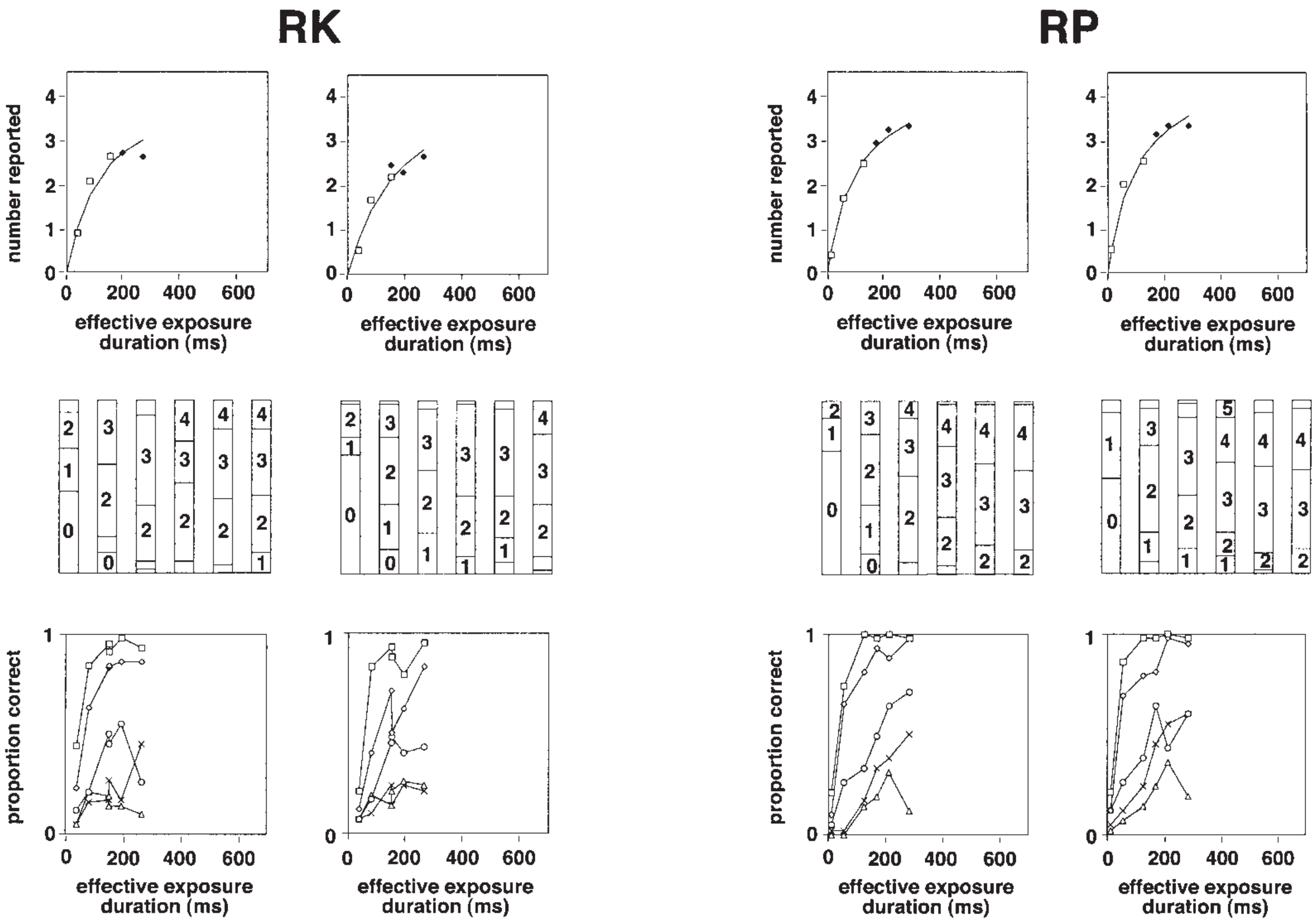

Figure 3. *Experiment 1: Data for patient (GK) and controls (remainder), separately for left (left panels) and right (right panels) visual fields. Upper panels: Mean number of letters reported as a function of effective exposure duration; open squares—masked exposures; filled diamonds—unmasked exposures; solid line—fit from TVA. Middle panels: Proportions of trials with 0, 1, . . ., 5 letters correctly reported for each effective exposure (increasing duration from left to right); for clarity, proportions below .10 are unlabelled. Bottom panels: Proportion correct as a function of effective exposure for each array position (order of positions from top to bottom—squares, diamonds, circles, triangles, crosses).*

0, 1, . . ., 5 letters correct, separately for each of the six effective exposure durations (within each panel, durations in increasing order from left to right). Lower panels show proportion of correct reports for letters in each array location, again as a function of effective exposure duration.

The data show several important features of GK's whole report deficit. The first concerns rate of processing, captured in TVA by the parameters C_L and C_R. The strong impression is that, by comparison with controls, processing rate was very much slowed in GK, with only very gradual improvements in performance as exposure duration increased (Figure 3, top panels). The second concerns maximum number of letters reported, captured in TVA by VSTM capacity K. While three or more letters were frequently reported by all controls (Figure 3, middle panels), GK fairly often reported two letters but very rarely three. Finally, GK's deficit concerned all display positions (Figure 3, bottom panels), with no evidence that poor overall performance resulted from excellent scores in certain positions at the expense of very poor performance elsewhere.

As described above, TVA was fitted to data for each participant and visual field. Best-fitting parameters for each data set appear in Table 2. In line with the above impressions, overall processing rates C_L and C_R were at least an order of magnitude lower in GK than controls. Separately for C_L and C_R, differences between GK and controls were tested by between-groups ANOVA (N = 1 for GK and N = 7 for controls), following a log transformation to eliminate outliers in the control distribution. Both differences were significant, $F(1, 6) = 35.0, p < .001$ (1-tailed) for C_L, $F(1, 6) = 21.4, p < .005$ for C_R. As shown by the separate v values in Table 2, this slowing of processing was seen at all locations on each side. Though slowed processing was the most conspicuous aspect of GK's deficit, by comparison with controls his VSTM capacity K was also somewhat reduced, $F(1, 6) = 4.1, p < .05$.

Discussion

In this experiment we measured two TVA parameters, processing rate C and VSTM capacity K. According to TVA, it is K that would most naturally be implicated in a primary inability to process more than one object or element in a visual array. While setting K equal to one would make it impossible to report more than one display element, processing of a single element would be unimpaired. Reductions in C, in contrast, should affect processing at all array sizes, including one.

Table 2. *Experiment 1: Model parameters*

	Left						*Right*								
Participant	v_1	v_2	v_3	v_4	v_5	C_L	v_1	v_2	v_3	v_4	v_5	C_R	K	t_0	μ
Patient															
GK	0	0	1	0	0	2	0	1	1	0	0	3	2.5	107	364
Controls															
CX	1	2	12	2	3	20	4	6	11	1	1	22	3.2	1	118
JT	6	3	6	2	3	19	7	3	3	2	3	18	3.3	0	146
FS	17	8	3	3	3	34	16	9	5	2	3	35	4.5	0	73
PK	9	6	5	3	3	26	9	12	7	2	3	33	3.6	0	80
RC	24	13	9	5	14	66	19	21	13	10	17	80	4.8	0	96
RK	17	10	3	1	2	33	13	6	3	1	1	24	3.8	5	113
RP	25	13	4	1	2	45	25	13	4	1	3	46	4.8	31	158

v_i = processing rate for element i (elements/s); C_L, C_R = total processing rate in left and right fields (elements/s); K = visual short-term memory capacity (number of elements); t_0 = minimum effective exposure duration (ms); μ = additional effective exposure for unmasked array (ms). Discrepancies between C_L, C_R and corresponding summed v values reflect rounding errors (all values rounded to nearest integer).

Certainly GK showed a major whole report deficit, affecting both masked and unmasked displays. In more detail, however, this deficit was rather surprising. Indeed, there was a modest reduction in *K*, significant by comparison with the group of seven controls. The estimated *K* value, however, was certainly not one—reflecting the finding that, at the longer exposure durations, GK actually reported two letters (occasionally even three) on around 15% or more trials. Instead, by far his most conspicuous deficit was an approximately 10-fold reduction in *C*, implying not any selective loss in ability to process multiple elements, but rather a massive overall slowing of visual processing.

Another possible account of poor performance—overwhelming bias towards one array location—is ruled out by these data. GK did not show a pattern of excellent performance for one location, accompanied by little to no identification of letters elsewhere.

One possible reservation over these conclusions concerns a technical detail of *C* estimation. As evident from Figure 3, GK's *C* estimate was partially dependent on the fit to data from unmasked displays. For such displays, the estimate of effective exposure duration depends in turn on the estimate of μ, the additional effective exposure of an unmasked display, and—as shown in Table 2—the μ estimate was very much greater in GK than controls. There is no direct reason to doubt this μ estimate. It would imply that the duration of iconic memory is substantially enhanced in GK or, complementarily, that his visual system is sluggish in responding to display offset. Furthermore, even masked data alone are strongly indicative of very slow processing in this patient (Figure 3). Still, in Experiment 2 we attempted to replicate a measurement of *C* deficit using only masked displays.

A second possible reservation over our conclusions concerns interpretation of TVA parameters. Though according to the theory a reduction in *C* should affect even single-element displays, the data of Experiment 1 obviously do not show this directly. In Experiment 3 we measured identification of single masked letters presented at fixation.

Experiment 2

In Experiment 2, GK was tested with six-letter masked displays, presented for variable duration. Letters were arranged in a circle around fixation.

Method

Procedures were as before, except as follows. In this experiment, there was no initial digit task to encourage central fixation. Instead, the display was initiated when GK was confident that he had located the fixation point. The display consisted of six letters, equally spaced around an imaginary circle of radius 3.2°, centred on fixation. There were five exposure durations (114, 271, 428, 585, and 742 ms), varying randomly across trials; all displays were immediately followed by a 500-ms mask consisting of the same mask characters as before in each display position. In this experiment, heights of letters and masks were 0.75 and 1.5° respectively. Across a number of sessions, GK completed a total of 475 trials.

Results

Results appear in Figure 4. Fits by TVA were obtained by similar procedures as before. This time,

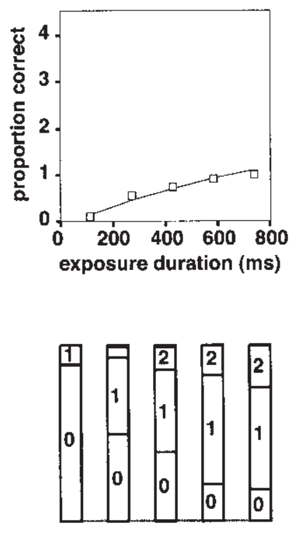

Figure 4. *Experiment 2: Data for GK. Conventions as for Figure 3, except upper panel: Data as a function of actual exposure duration rather than estimated effective duration.*

there was only a single estimated value of *C* (summed *v* values across the six display positions). As all displays were masked, there was no estimate of μ; data in Figure 4 are plotted as a function of actual exposure duration rather than estimated effective duration. As shown in the upper panel, processing again was very slow, with a *C* estimate of only two elements/s. Examination of data for the six different display positions (not shown) showed that this held true for all positions; even for the best position (top right), probability of correct report rose only slowly across exposure durations, to a maximum of around 0.5. As in Experiment 1, GK commonly reported two letters but only rarely three (Figure 4, lower panel); the estimate of *K* was 2.2, again very close to the estimate from Experiment 1. For this experiment, t_0 was estimated at 51 ms.

Discussion

In Experiment 2, GK's major deficit in processing rate was confirmed using only masked displays. Evidently, the *C* estimate in Experiment 1 was not strongly dependent on the fitting procedure used to combine data from masked and unmasked trials.

Experiment 3

In Experiments 1 and 2, GK's processing of multi-letter arrays was remarkably slow. According to TVA, such slowing reflects impairment in processing rate *C*. A strong prediction is that processing should also be slow for a single letter array. In Experiment 3, this was tested with single letters presented directly at fixation.

Certainly, TVA's account of processing rate impairments could be incorrect. A common proposal, for example, is that parietal lesions produce a deficit in attentional "disengagement," or removal from the current focus (Posner, Walker, Friedrich, & Rafal, 1984). This idea is reminiscent of the concept of "sticky" perception in simultanagnosia (Kinsbourne & Warrington, 1962); more generally, the idea is that the first element is processed normally in a visual array, but moving on to further elements is impaired. As we said earlier, one possible way to incorporate such proposals into TVA might be reduction in *K*. A disengage deficit could also be manifest, however, as slowed processing rate only in multi-element displays, a finding that TVA could not incorporate very easily.

As mentioned above, dorsal simultanagnosia has also sometimes been interpreted as a bilateral version of sensory extinction, i.e., an elimination of processing in the visual periphery due in part to foveal bias. This account predicts little impairment in processing of single, foveally presented letters.

Method

Participants. In addition to GK, data were obtained for six healthy controls, five women and one man, aged between 26 and 73 years (mean 52).

Task and procedure. For this experiment the monitor background was set to pale grey. Again there was no precise control of viewing distance, so reported visual angles are approximate.

Again, each trial began with an unscored digit task designed to encourage central fixation. At trial onset, a red fixation cross, height 1.7°, was centred on the screen. When the experimenter pressed a key, this cross flashed off for 108 ms, on for 108 ms, off for 108 ms, on for 108 ms, off for 108 ms, on for 108 ms, then was replaced by a small (0.6°) red digit, centred on fixation. This remained for 314 ms, after which the fixation cross returned while the participant named the digit. Again, digit responses were not recorded or scored.

On a second keypress from the experimenter, the main target was immediately presented. It was a black letter, 3.7° in height, again centred on fixation, randomly drawn from the set BCDFHJKLNPSTXZ. After a variable exposure duration, it was immediately replaced by a 206-ms mask, a dense patch of jumbled black lines covering the same area as the preceding letter. The fixation cross then returned while the participant attempted to name the letter, with omissions permitted. As in previous experiments, responses were unspeeded, and typed into the computer by the experimenter.

As all events were foveal in this experiment, eye movements were not carefully assessed. For GK, three trials with evident head movements were discarded.

Testing took place in blocks of 40 trials, with 8 trials at each of 5 exposure durations per block, in random order. Controls were given a total of 6 blocks, spread over 3 testing sessions devoted to several different tasks. Their exposures were always nominally 20, 40, 70, 100, and 150 ms (in fact .98 of these values owing to the monitor refresh rate). GK was also given 6 blocks, in a single session. For the first and last block, nominal exposures were as for controls; for remaining blocks, they were 70, 100, 150, 200, and 250 ms.

Results

Individual results for each participant appear in Figure 5. Again, the data are plotted as a function of actual exposure duration rather than estimated effective duration. At least for controls, functions are approximately exponential in form, as predicted by TVA. For GK, the data show a massive reduction in speed of processing, with a proportion correct of only .84 even at 250 ms exposure.

Exponential functions were fit separately to the data for each participant by least squares (using nominal exposures as reported above). Best fitting parameters appear in Table 3. For this experiment there is only a single rate parameter (v value), reflecting processing rate for the single foveal letter. By comparison with Experiments 1 and 2, processing was generally faster here, as expected for large foveal letters. Again, however, GK showed close to a 10-fold reduction in rate by comparison with controls, $F(1, 5) = 39.6$, $p < .001$ (following log transformation).

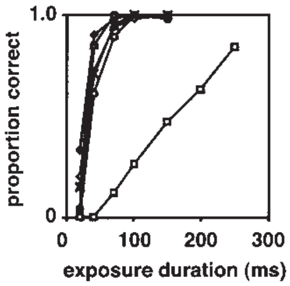

Figure 5. *Experiment 3: Proportion correct as a function of exposure duration for GK (squares) and controls (other symbols).*

Table 3. *Experiment 3: Model parameters*

Participant	v	t_0
Patient		
GK	8	58
Controls		
AB	52	16
BP	47	20
CW	87	18
FB	54	17
PC	92	16
JB	95	20

v = processing rate for single foveal letter (elements/s);
t_0 = minimum effective exposure duration (ms).

Discussion

In Experiment 3, GK showed major impairment in processing even a single foveally presented letter. Indeed, his deficit seemed at least as marked here as in earlier experiments with multi-letter arrays. Again, this deficit is better described as a general reduction in processing rate than as selective difficulty with multiple array elements.

Experiment 4

Closely related to the concept of "simultanagnosia" is "divided attention decrement," or reduced performance when several array elements must be processed at once. At face value, simultanagnosia implies unusual decrement, or an unusually large difference between processing one vs. two or more elements. As we have seen, GK's impairment clearly affects both single- and multi-element displays. In Experiment 4 we asked whether his divided attention decrement—specifically, the difference in accuracy with 1- and 2-letter displays—is in fact abnormal.

As we show below, this question may be posed quite exactly within TVA. Assume that $K > 2$ (which we have already confirmed for GK and the control participants in Experiment 1, who served again in Experiment 4); now performance depends only on the competitive processing defined by Equations 1 and 2. Given single-element accuracy (Equation 1) and weight ratio (Equation 2), TVA predicts the exact performance level in a two-element display. In other words, TVA can make exact predictions concerning the magnitude of divided attention decrement. In Experiment 4, we assessed its ability to fit data from both GK and controls.

For this purpose, it is useful to consider performance at just a single exposure duration t. For a display consisting of a single element i followed by a mask, Equation 1 now simplifies to

$$P_i = 1 - \frac{1}{e^{A_i}} \quad (3)$$

where $A_i = s_i(t - t_0)$. For fixed exposure, A_i is proportional to s_i and so again can be taken as a measure of basic sensory efficiency. For a display consisting of two elements i and j, we have

$$P_i = 1 - \frac{1}{e^{A_i w_i / (w_i + w_j)}} \quad (4)$$

$$P_j = 1 - \frac{1}{e^{A_j w_j / (w_i + w_j)}} \quad (5)$$

Thus, given measures of accuracy for both i and j in both one- and two-element displays, we can ask whether there exist estimates for A_i, A_j, and the two weight ratios which provide a good fit to the data—with the constraint that weight ratios must sum to 1.

In practice, the design of Experiment 4 was slightly more complex. Instead of just two display locations we used four, arranged in a square centred on fixation. Furthermore, the task was a variant of *partial report* (Bundesen, 1990; Sperling, 1960)—in some blocks the task was to identify red letters while ignoring green letters, in other blocks the reverse. There were three types of display. First, targets occurred alone, in each of the four possible display locations. Second, pairs of targets were presented together, either in the same hemifield (upper left + lower left or upper right + lower right), or in opposite hemifields (upper left + upper right or lower left + lower right; no diagonal displays were used.) For these displays both targets were to be reported, in either order. Third, a single target could be accompanied by a single nontarget, again either in the same hemifield or in opposite hemifields (again without diagonals). In total this produces 16 trial types—4 one-target (upper left, lower left, upper right, lower right), 4 two-target (upper left + lower left, upper right + lower right, upper left + upper right, lower left + lower right), and 8 target + nontarget (the same four pairs of locations, each with either location containing the target). Separately for each participant, fits to TVA were obtained using straightforward extensions of Equations 3–5 (see Duncan et al., 1999). For each location i, best-fitting estimates were obtained for measures of sensory effectiveness A_i, attentional weight of a target $w_i(T)$, and attentional weight of a nontarget $w_i(N)$, with estimates varying freely between locations.

While our major goal was to test the adequacy of TVA fits—and, specifically, TVA's ability to capture the overall difference between one-target and two-target displays—the data are potentially relevant to two further issues. First is lateral attentional bias: As noted above, GK shows a tendency to extinguish the left-sided stimulus under bilateral simultaneous stimulation. We expected to see this same tendency here with upper left + upper right or lower left + lower right displays. In TVA, such a result would be reflected in low estimates of attentional weight for left-sided letters.

Second, we used partial report with the intention of measuring top-down control, or differential weighting of target and nontarget letters. In fact, poor performance of some controls (see data for these same participants in Duncan et al., 1999) prevented useful conclusions about GK. As some controls showed essentially zero top-down control—i.e., equal weighting for targets and nontargets—it was impossible for GK's performance to be worse. Though data from target + nontarget displays were used in estimating TVA parameters (see above and Duncan et al., 1999), they will not be considered further.

Method

Experiment 4 was run on the same participants as Experiment 1, in interleaved sessions. Except as noted, procedures for the two were similar. As described above, letters in Experiment 4 were presented at the corners of an imaginary square, 4.7 × 4.7°, centred on fixation. In different blocks, the task was either to identify red letters and ignore green letters, or vice versa. Again, participants were asked to report identities (not locations) for just those targets they were fairly confident of, and thus reported 0, 1, or 2 on each trial. For displays with two targets, e.g., upper left + lower left, proportion correct was scored separately for each position. For each participant there was only a single exposure duration, selected after an initial practice session to produce accuracy in the range 60–90% in one-target displays. For GK, this exposure was 500 ms, while for controls it was either 57 (RC) or 71 (others) ms. All displays were immediately followed by a 500-ms backward mask, constructed of four masking characters like those in Experiment 1, one in each display location.

The same procedure for encouraging central fixation was used as in Experiment 1. Again GK had little trouble fixating, with only nine trials excluded for eye movements. Overall, GK completed approximately 31 trials for each of the 16 trial types (see above), while controls completed between 32 and 39.

Results

Results for each participant appear in Figure 6 (solid lines). Proportion correct is shown separately for targets in left (left panels) and right (right panels) hemifields, presented alone, with an additional target in the same hemifield, or with an additional target in the opposite hemifield. In each case, data from upper and lower positions have been averaged. Predictions from the best-fitting set of TVA parameters for each participant are also shown (dotted lines).

The first noteworthy result concerns the overall difference between one- and two-target displays. In all cases but one (CX, right field, additional target in opposite hemifield), there is the expected divided attention decrement. For both GK and controls, this decrement is well fit by TVA. In GK, the fit accounted for 96% of the variance between all data points (separate data for all four positions and all display types, including target + nontarget), root mean squared deviation (RMSD) .06. In controls, fits accounted for 59–95% of the variance, RMSD .05 to .08.

A second noteworthy result is GK's expected left-sided extinction. When targets were simultaneously presented to left and right (Figure 6, +opp data points), performance for the left-sided target was particularly poor, while performance for the right-sided target was relatively preserved. In TVA's fits, attentional weights were separately estimated for targets and nontargets in each display position. To capture attentional bias, a useful index (Duncan et al., 1999) is $w_L/(w_L + w_R)$, where w_L is mean estimated attentional weight for all items on the left, and similarly for w_R on the right. Values of this index are shown for each participant in Table 4. As expected, GK's value was below that of all controls, $F(1, 6) = 3.6$, $p < .06$ (1-tailed), indicating lower attentional weights on the left.

Discussion

In Experiment 4, roughly comparable performance in one-target displays required much longer exposures for GK than for controls. This is the result expected from a reduction in *C*, and from the results of Experiment 3. In contrast, GK and controls showed comparable decrements from one- to two-target displays, well fit by TVA. Once more, the impression is not of primary difficulty with processing more than one letter, but of simple overall reduction in processing speed.

Table 4. *Experiment 4: Weight ratios*

Participant	$w_L / (w_L + w_R)$
Patient	
GK	.33
Controls	
CX	.38
JT	.44
FS	.54
PK	.57
RC	.45
RK	.54
RP	.42

For definition of weight ratio see text.

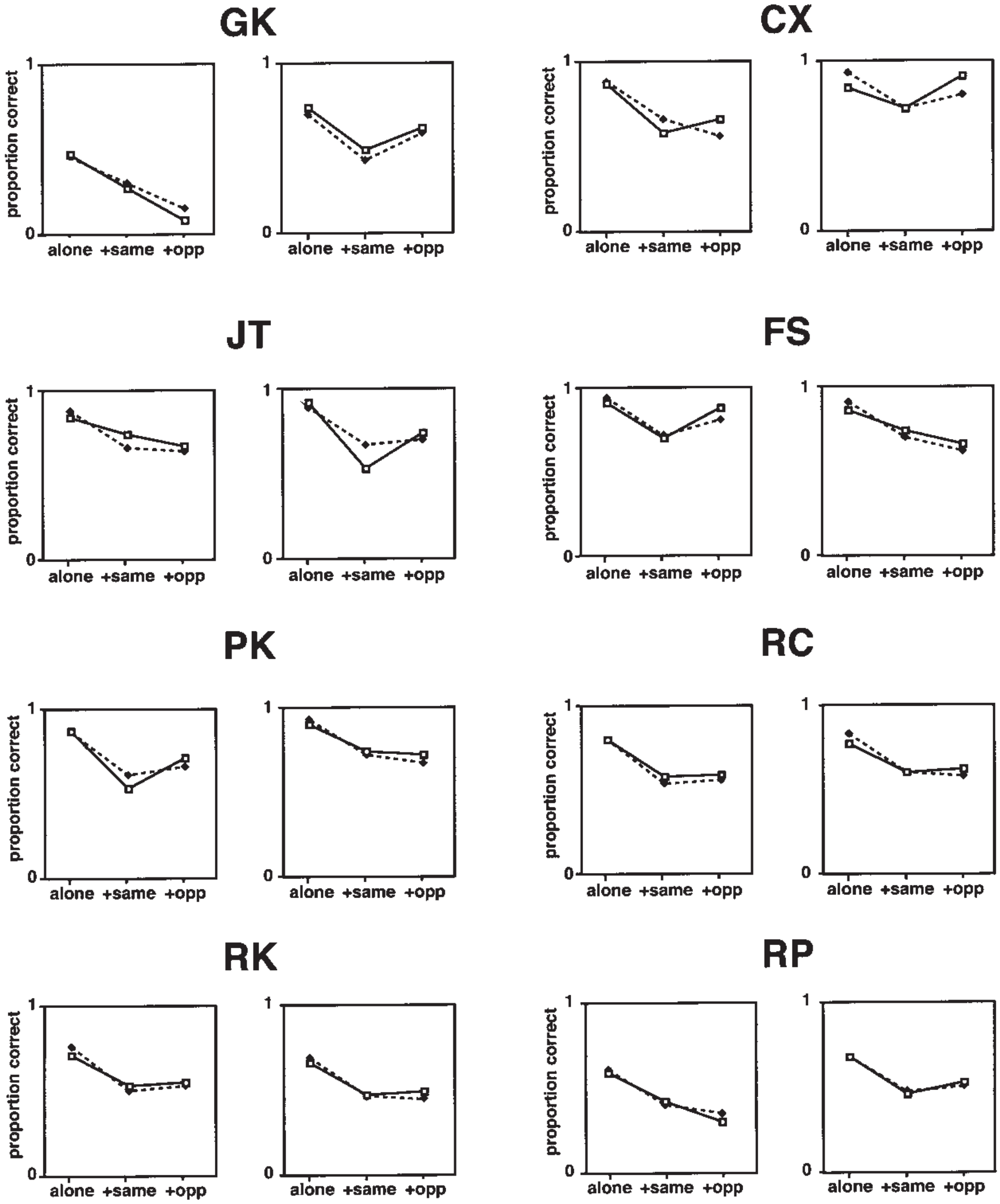

Figure 6. *Experiment 4: Proportion correct for patient (GK) and controls (remainder), separately for targets in left (left panels) and right (right panels) visual fields. Targets are presented alone, with a second target in the same visual field (+same), or with a second target in the opposite visual field (+opp). Solid lines—data; dotted lines—predictions.*

GK: General discussion

Together, Experiments 1 to 4 assessed three different accounts of GK's dorsal simultanagnosia. In TVA, these would be distinguished by impairment in different processing parameters.

Most obviously, simultanagnosia might be reflected in reduced VSTM capacity, and specifically in a K value of 1. With a brief display, such a deficit would leave processing of a single display element unimpaired, but make it impossible to report more than one. Indeed, GK showed a reduction in K by comparison with controls. His estimated value, however, was greater than 2, reflecting his report of two and occasionally even three letters on some whole report trials. These data do not imply a primary deficit in processing multiple display elements.

A second possibility is disordered attentional weighting. If some positions received much higher attentional weights than others, the result could be good performance for just the favoured position in a multi-element display, but little or no identification of elements elsewhere. Indeed, GK showed a mild disorder of attentional weighting, with stronger weights on the right. But this was not relevant to his primary disorder, reflected in poor performance even with vertical whole report arrays (Experiment 1), and with just a single letter at fixation (Experiment 3).

Instead, the data tell a fairly clear story of impaired processing speed, at all display sizes, revealed by a massive reduction in C. As anticipated by Bálint (1909/1995), Luria (1959), and others, the suggestion is of a general weakening in visual processing. Though failures will, of course, be most conspicuous in demanding, multi-element displays, there is already a major impairment with just a single display element. Indeed, Experiment 4 shows directly that the decrement from one- to two-target identification in itself is not abnormal.

VENTRAL SIMULTANAGNOSIA

The patient

MP, an English teacher, suffered a stroke at age 56. A CT scan 2 weeks later showed a large lesion of the left occipital lobe, extending forward into the posterior temporal lobe (Figure 2).

A highly educated man, MP continued to perform in the high average to superior range in tests of intellectual function, even in the period immediately post-stroke. In identification of single letters he scored 38/40 correct. His reading, however, was strikingly slow, with the characteristic letter-by-letter pattern of ventral simultanagnosia. For single irregular words, reading times were 20 s or more. He was also blind in the upper right visual quadrant.

Over the succeeding months, MP's reading gradually improved, though not to the premorbid level. The current experiments were run approximately 1.5 years after his stroke. He thus represents the usual partial recovery from an early ventral simultanagnosia/pure alexia (see, e.g., Behrmann & Shallice, 1995).

Experiment 5

Experiment 5 used the same whole report method as Experiment 1. Again, it addresses processing rate C, VSTM capacity K, and positional bias, all for columns of letters in left or right hemifield.

Method

Procedures were similar to Experiment 1. Like GK, MP had no trouble maintaining central fixation; one trial was excluded for eye movement. MP's exposure durations were 29, 100, and 171 ms, again used with and without masks. In total he completed 768 trials.

Results

MP's results are shown in Figure 7. By comparison with the controls from Experiment 1 (Figure 3), his processing was again somewhat slowed (upper panels). For the left field, he often reported three letters, and once four (middle left). For the right field he never reported more than two (middle right), being blind for the upper three positions (bottom right). Otherwise, his positional preferences (bottom panels) were not unusual.

Fits to TVA were obtained after removing the one trial with four letters reported as an outlier (for outlier definition see Duncan et al., 1999; outliers were not found in controls). Best-fitting parameters appear in Table 5. As for GK, comparison with controls showed significant impairments in both C_L, $F(1, 6) = 5.4$, $p < .05$, and C_R, $F(1, 6) = 8.5$, $p < .02$ (both tests 1-tailed, following log transformation). The modest K reduction was of borderline significance, $F(1, 6) = 3.4$, $p < .06$. Inclusion of the outlier trial produced very similar results, except that the K estimate increased to 3.2.

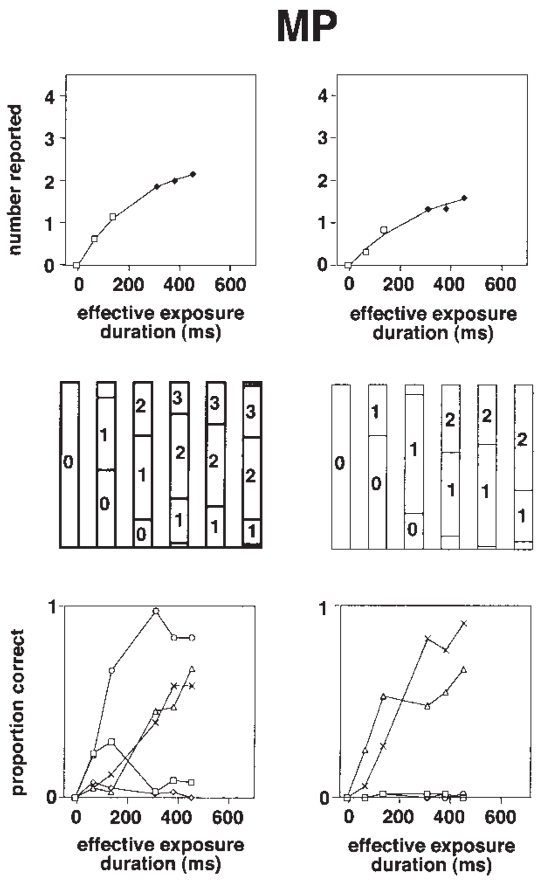

Figure 7. *Experiment 5: Data for MP. Conventions as for Figure 3.*

Discussion

Though less severe, MP's whole report impairment was essentially similar to that shown by GK. Again, there was a reduction in K, but not so severe as to produce general inability to report more than one letter from a display. Instead, the most conspicuous feature of the deficit was a reduction in processing rate.

Strikingly, overall processing rate was almost equally affected in the two hemifields. Though the lesion effectively produced complete blindness for the top three positions in the right visual field, this was compensated for by relatively strong performance in the remaining two. This is the result we should expect if overall processing rate is similar on the two sides, but with the upper right letters eliminated as competitors (cf. Equation 2). Thus the most striking result of a left occipital lesion is substantial bilateral impairment in overall rate of uptake of visual input—very similar, indeed, to the effect of GK's extensive bilateral lesions.

Experiment 6

Experiment 6 used the partial report task of Experiment 4. Again, the data presented here concern just one- and two-target displays, bearing on the absolute size of divided attention decrement and

Table 5. *Experiment 5: Model parameters*

	Left						Right								
Participant	v_1	v_2	v_3	v_4	v_5	C_L	v_1	v_2	v_3	v_4	v_5	C_R	K	t_0	μ
Patient															
MP	1	0	6	2	2	11	0	0	0	3	4	7	2.7	36	316

v_i = processing rate for element i (elements/s); C_L, C_R = total processing rate in left and right fields (elements/s); K = visual short-term memory capacity (number of elements); t_0 = minimum effective exposure duration (ms); μ = additional effective exposure for unmasked array (ms).

(when two targets appear in opposite hemifields) on lateral attentional bias.

Method

Procedures were similar to Experiment 4. Again, MP completed 768 trials, with just 1 excluded for eye movement. Exposure duration was 128 ms with masking.

Results

Results appear in Figure 8. As MP was blind in the upper right quadrant, only data for targets in the lower visual field (left and right) are presented. Thus the figure shows proportion correct for these targets presented alone, accompanied by a second target on the same side (hence in the upper field), or accompanied by a second target on the opposite side (hence also in the lower field).

In three cases out of four, two-target displays showed the usual divided attention decrement. The exception concerns targets in the (lower) right field accompanied by a second target on the same side; as this second target fell in the blind (upper) quadrant, it had no effect on lower-field accuracy. Apart from this, the overall performance difference between one- and two-target displays was not unusual, and was well fitted by TVA. The fit accounted for 99% of the variance between all data points (separate data for all four positions and all display types, again including target + nontarget), RMSD .03.

Displays with one target in each hemifield showed a strong pattern of contralesional extinction. For the left field target, the decrement from

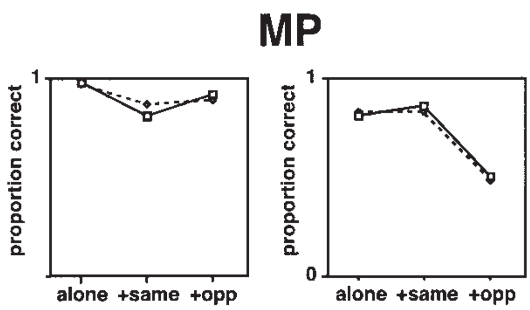

Figure 8. *Experiment 6: Data for MP. Conventions as for Figure 6.*

one-target accuracy was very small (Figure 8, left panel, +opp vs. alone); for the right field target, it was substantial (Figure 8, right panel, +opp vs. alone). To capture this bias away from the contralesional field, we used the index $w_R/(w_L+w_R)$, calculated as previously decribed from TVA's estimated attentional weights for lower-field display items. The index of .26 differed significantly from that of the seven controls from Experiment 4, $F(1, 6) = 11.6$, $p < .01$.

Discussion

In milder form, MP's overall impairment in Experiment 6 resembled that shown by GK in Experiment 4. As compared to the Experiment 4 controls, MP required a somewhat longer exposure duration for equivalent one-target performance. Given this, however, the two-target decrement was quite normal. Again, the data do not suggest primary difficulty with processing of multiple display elements.

The second result concerns attentional bias. In line with other studies of ventral simultanagnosia (e.g., Behrmann & Shallice, 1995; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978; Rapp & Caramazza, 1991), the data showed bias to the left ipsilesional field.

MP: General discussion

Overall, MP's results were strikingly similar to those of GK. By comparison with controls, there was a modest impairment in *K*, a marked reduction in *C*, a normal overall divided attention decrement, and a lateral attentional bias, here favouring the left. For the basic visual functions measured in TVA, the data suggest rather similar impairments in dorsal and ventral simultanagnosia.

GENERAL DISCUSSION

Primary processing deficits in simultanagnosia

Together, the results of these experiments suggest something surprising about "simultanagnosia." According to TVA, either disordered short-term memory or disordered attentional weights could lead to specific impairment in processing more than one visual display element. A *K* value of 1 would have no influence on processing a single display element, but would make it impossible to identify two or more. Strong attentional focus on one display region, e.g., foveal dominance, would also have little effect until two or more elements were in competition. For both of our patients, indeed, the data showed impairments in both VSTM capacity and attentional weighting. In neither case, however, were these the primary deficits. Instead, the most prominent result was a simple reduction in processing speed, which at least in GK affected even a single letter presented directly at fixation.

In the literature, as we have seen, there is evidence in different cases that poor single element processing (Bálint, 1909/1995; Kinsbourne & Warrington, 1962; Luria, 1959), spatial bias (Kinsbourne & Warrington, 1962), and *K* values close to 1 (Coslett & Saffran, 1991; see also Pavese, Coslett, Saffran, & Buxbaum, 2002) can all contribute to simultanagnosia. The present cases, however, suggest that the dominant factor may often be processing speed rather than a specific impairment in simultaneous perception.

Can such an account deal adequately with the clinical phenomena of simultanagnosia? In a cluttered visual world, with multiple elements simultaneously competing to be processed, it is plausible that often only the strongest one will survive a massive reduction in processing rate, others failing to complete even with long exposures. Either because of stronger attentional weights at the fovea, or simply because of better sensory input and thus higher *v* value, this surviving element might often be the element that is fixated. Bálint (1909/1995), for example, described that ". . . fixating a needle made it impossible for (the patient) to perceive a candle light placed at a 5 cm distance from him" (p. 269). Any kind of differentiation in attentional weights, however, could produce similar results. When GK is shown overlapping pictures and words, for example, he very commonly reports just the picture (Humphreys et al., 1994), a result that could easily follow from impaired processing rate accompanying greater attentional weight for pictures. A greater attentional weight for moving or newly appearing objects (Yantis & Hillstrom, 1994) could explain how, for Luria's (1959) patient, a sheet of paper seemed to disappear when a moving pencil tip approached. In a competitive visual world, it is easy to see how a primary deficit in processing speed might often translate into outright failure to see any objects but the one or two most dominant.

Letter-by-letter reading

For ventral simultanagnosia, perhaps the most conspicuous clinical deficit is letter-by-letter reading. Accounts of this phenomenon fall into two broad classes. In the first type of account, the central deficit is specific impairment in word perception, e.g., impairment in a visual word-form system (Warrington & Shallice, 1980). In the second, letter-by-letter processing reflects adaptation of reading to a broader visual deficit (e.g., Farah & Wallace,1991).

Evidently, an account in terms of TVA's rate parameter *C* falls into the second category. If processing is slow, one reasonable solution might be to minimise competition by top-down selection of one display location after another. This could be especially important if attentional weights are somewhat biased to the left (e.g., Behrmann & Shallice, 1995; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978; Rapp & Caramazza, 1991), tending to focus even what processing there is on the early letters in a word. Indeed, the basic account of letter-by-letter reading as just one manifestation of a broader "ventral simultanagnosia" presumes a deficit outside word recognition itself.

On its own, however, this account leaves something out. Like other ventral simultanagnosics, our patient MP read words letter by letter in the early period after his stroke. Despite an even more severe reduction in *C*, GK, like other dorsal simultanagnosics, does not read in this way. On the contrary, he has a form of "attentional dyslexia" (Shallice & Warrington, 1977), reading whole words quite successfully, but having difficulty identifying the separate letters in their correct positions (Hall, Humphreys, & Cooper, 2001).

In all likelihood, the issue here turns on what counts as a single, competing "display element" for TVA. Like other object-based theories (Duncan, 1984), TVA presumes that some visual grouping process determines what parts of the visual input belong together as parts of a single object, and that it is the objects so created that serve as the theory's competing "display elements" (Bundesen, 1990). In dorsal simultanagnosia, as in normal vision, grouping strongly determines the nature of attentional competition. Luria's (1959) patient, for example, could perceive the whole Star of David when it was drawn in a single colour, but saw only one component triangle or the other when one was red and the other blue. In word perception, it is commonly presumed that learning has bound component letters into a single familiar object, releasing them from the competition that unrelated letters would suffer (Siéroff & Posner, 1988). For GK and other dorsal simultanagnosics, we would suggest that this binding remains intact. No doubt word perception is slowed, but as regards competition, words act as single display elements. For MP and other ventral simultanagnosics, with their characteristic left occipital lesion, we would suggest that reduction in *C* is complicated by an additional, specific deficit in word recognition itself. Because of this deficit, even letters in familiar words suffer some of the same processing competition as unrelated display elements. Hence a basic visual impairment, in itself similar to that in dorsal simultanagnosia, is especially evident in word recognition.

Relationship to neglect

In a previous study, we used similar methods to analyse attentional impairments associated with left visual neglect (Duncan et al., 1999). In these patients, there were lesions affecting the right inferior parietal lobule (IPL), often extending into the posterior frontal lobe and/or superior temporal lobe. Two similarities to the present results are noteworthy.

The first concerns processing rate *C*. As in the present two patients, the IPL group showed a major *C* reduction in whole report. Again this was evident even with vertically aligned arrays, and though it was somewhat stronger in the left (contralesional) field, the major effect was bilateral. Though these were patients selected for left-field neglect, their most obvious impairment was slow processing in both visual fields.

Because of the bilateral parietal lesions, it has sometimes been supposed that Bálint's syndrome is a bilateral version of neglect (Harvey & Milner, 1995). For GK, indeed, whole report on both sides resembles the contralesional performance of the worst neglect patients (Duncan et al., 1999), in line with this interpretation. MP's data, however, show that much the same bilateral reduction in *C* can result from a quite different lesion, in the left occipital lobe. In all probability, overall processing rate is determined by several interacting influences. *C*, of course, reflects the efficiency of pattern recognition, and it is plausible that a left occipital lesion should have a direct effect on a letter recognition system processing material from both visual fields. This seems less plausible for a right inferior parietal lesion; here we may be dealing with some more general contribution to construction of a conscious percept (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Downar, Crawley, Mikulis, & Davis, 2000).

The second similarity with the neglect data concerns attentional weighting. In neglect patients, as expected, there was a reduction of attentional weights on the left, reflecting contralesional extinction. Again, MP's data show that a similar lateral bias can also follow from a left occipitotemporal lesion. As other data confirm (e.g., Vallar et al., 1994), a tendency to extinction—lateral attentional bias with competing inputs on the two sides—can doubtless be the result of many different lesions, in some cases even those outside the central nervous system (Bender, 1952; see also Duncan, 1996).

In recent work, a number of temporal processing deficits have been associated with parietal lesions and/or neglect. One example is impaired temporal order judgment, such that ipsilesional events appear to be seen earlier than similar contralesional events (Rorden, Mattingley, Karnath, & Driver, 1997). Another is lengthened "attentional blink," or period of impairment in identifying a second target stimulus when it follows shortly after a first

(Husain, Shapiro, Martin, & Kennard, 1997). Though these have some similarities with data indicating reduced processing speed, we would be cautious in proposing any direct correspondence. In normal subjects, for example, "processing" in the sense defined by TVA—entry of a stimulus description into VSTM—typically completes over tens of milliseconds from stimulus onset, while the attentional blink lasts hundreds of milliseconds. Further work is needed to address relations between these different temporal phenomena, in both normal subjects and parietal and/or neglect patients.

Conclusion

In this paper, we have tried to show the merit of analysing simultanagnosic impairments with a well-specified theory of normal attentional functions. In the context of TVA, many previous suggestions concerning simultanagnosia can be formalised and related, including proposals of primary deficit in processing multiple stimuli, attentional "stickiness," foveal bias, and bilateral neglect. Interestingly, the account fitting our cases is closest to Bálint's (1909/1995) and Luria's (1959) ideas of general weakening in visual representations. Rather than a true "simultanagnosia," there is a general slowing of visual processing, producing perceptual failure for all but the most dominant elements in a complex, cluttered, visual world.

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