



# Fractionating the binding process: neuropsychological evidence distinguishing binding of form from binding of surface features

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## Abstract

We present neuropsychological evidence demonstrating that the binding of form elements into shapes dissociates from the binding of surface detail to shape. Data are reported from a patient with bilateral parietal lesions, GK, who manifests left-side visual extinction along with many illusory conjunctions when asked to discriminate both surface and form information about stimuli. We show that there are effects of grouping on both extinction and illusory conjunctions when the tasks require report of object shape. In contrast, illusory conjunctions involving surface and form information were unaffected by grouping based on shape. In addition, grouping was stronger when forms were presented within the same hemifield than when they appeared in different hemifields, whilst illusory conjunctions of form and colour occurred equally often within and across hemifields. These results support a two-stage account of visual binding: form elements are first bound together locally into shapes, and this is followed by a second stage of binding in which shapes are integrated with surface details. The second but not the first stage of binding is impaired in this patient. © 2000 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

There is considerable physiological and psychological evidence indicating that early stages of vision involve the decomposition of the image along a number of independent dimensions. For example, single cell recording studies have demonstrated the existence of multiple visual areas in the cortex, with the cells in the different areas responding selectively to the colour, shape and movement of stimuli (e.g. Cowey, 1985; Zeki, 1993). Such studies are matched by data from human functional imaging (Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1991; Corbetta, Shulman, Miezin & Petersen, 1995). Psychological evidence comes from studies of visual search and selective attention, showing that people can selectively search for and attend to some dimensions of stimuli with little effect of

variations along other dimensions (e.g. Garner & Felfoldy, 1970; Garner, 1974). Despite this evidence, the processes by which visual elements become bound, to generate coherent visual perceptions, remain poorly understood. In this paper we present new neuropsychological evidence indicating that the processes involved in binding together shapes can be separated from those involved in binding surface properties to shapes. The results argue for a two-stage process of binding, in which form elements are grouped prior to the integration of form and surfaces. The prior binding of form elements into primitive object descriptions enables object coding to influence the binding of surface information in vision.

### 1.1. Theories of binding

Two currently influential accounts suppose that binding in vision is determined either by attention to spatial location or by temporal co-occurrence of features.

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### 1.1.1. Feature integration theory (FIT)

FIT holds that visual elements are bound by attention to their common location (e.g. Treisman, 1988; Treisman & Gormican, 1988; Treisman, 1998). Detectors within individual feature maps (e.g. for the colour green, or for a vertical orientation) are linked to units in a ‘master map’ of locations to which attention is applied. By attentional excitation of their common location, attended features are activated over non-attended features; this enables a bound conjunction of attended features to access stored memory representations of objects.

Evidence for FIT comes from various sources. For example, numerous studies have shown that visual search for a target defined by a conjunction of features (e.g. a blue H amongst blue As and green Hs) typically fits a pattern predicted by serial search models (e.g. Treisman & Gelade, 1980; Quinlan & Humphreys, 1987; Wolfe, 1994; though see Townsend, 1971; Humphreys & Müller, 1993, for alternative accounts of the same data set). Serial search of one conjunction at a time is predicted if participants need to attend to the location of each item to bind the features together. Also, when participants are prevented from attending optimally to displays, illusory conjunctions can arise in perceptual report. Treisman and Schmidt (1982) used displays such as those used in Fig. 1. The task was to attend to and report the numbers present and then to report the shape, size and colour of the item that had appeared at a location cued by a later bar marker. They found that participants made errors by apparently miscombining the shape, size or colour of cued and non-cued items in the displays (e.g. reporting a green rather than a red circle, for a display such as that shown in

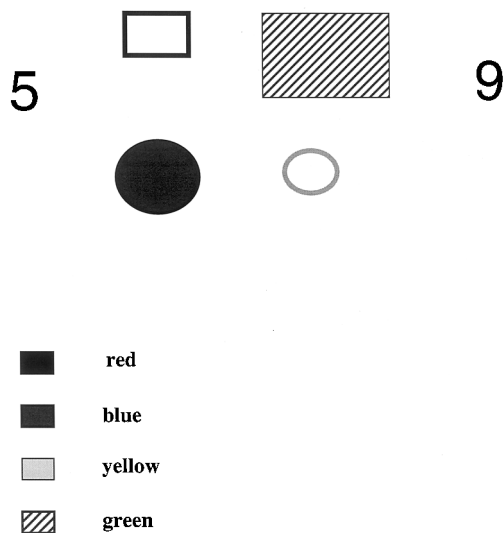


Fig. 1. Stimulus displays such as those used by Treisman and Schmidt (1982). The task was to report the identity of the two digits first and then as many features as possible in a location cued by a bar marker.

Fig. 1). These illusory conjunctions occurred on about 18% of the trials whereas errors due to the report of features not present in the displays (e.g. an orange circle) occurred on only about 6% of the trials. The illusory conjunction errors can arise under forced choice as well as free report conditions, suggesting that they have a genuine perceptual origin (e.g. rather than arising in memory; though see Ashby, Prinzmetal, Ivry & Maddox, 1996; Donk, 1999, for alternative views). According to FIT, illusory conjunctions should arise when participants are unable to attend to the common location of the features present in an object, to bind the features together.

Neuropsychological evidence consistent with FIT has come from studies of patients with parietal lesions, who seem to have difficulty both in visual search for conjunctions and in perceptual report tasks (where abnormally large numbers of illusory conjunction errors arise). For instance, Friedman-Hill, Robertson and Treisman (1995) and Robertson, Treisman, Friedman-Hill & Grabowecy (1997) reported data on a patient with Balint's syndrome following bilateral parietal lesions. Although able to detect salient single feature targets in parallel across visual displays, this patient was severely impaired at conjunction search (see also Humphreys & Price, 1994). Also, even under free viewing conditions the patient generated illusory conjunction errors by mis-combining the shapes and colours of stimuli present. Friedman-Hill et al. (1995) argued that the parietal lesions suffered by their patient disturbed the operation of attention within the master map of locations, with the result that there was an impairment in the binding process. Due to the problem in binding there was both poor conjunction search and abnormally high numbers of illusory conjunctions when multiple objects were present.

### 1.1.2. Pre-attentive binding

Although FIT enjoys considerable success in accounting for both ‘serial’ functions in conjunction search and illusory conjunctions under attentional load conditions, other data are problematic. For example, several studies of search suggest that features can be bound pre attentively, in a spatially parallel manner. Thus Enns and Rensink (1991) demonstrated relatively efficient (spatially parallel) search for line drawings of targets differing in three-dimensional (3D) orientation from distractors, even though the 3D orientation of the shapes could only be derived from binding together the 2D line elements. Humphreys and Donnelly (in press) used a task in which participants searched for a target placed at one of the vertices making up a 3D or a 2D shape. They found that 3D shapes derived from grouping between the vertices were robust to small rotations in the vertex elements whereas search with 2D shapes was disrupted. They proposed that 3D shape informa-

tion is rapidly derived from appropriate arrangements of form elements, and that it provides a useful constraint in binding elements together in parallel. Rensink and Enns (1995) have further shown that search for a target element can be difficult if it binds with other elements present. For example, search for a long line amongst smaller lines is difficult if the lines are arranged with fins that reduce the apparent size difference between the stimuli (e.g. using modified Müller-Lyer type stimuli). These results are all consistent with some form of spatially parallel binding of visual elements, prior to the operation of serial attentional processes in vision.

Studies have also demonstrated effects of grouping and stored knowledge on illusory conjunctions, though according to FIT illusory conjunctions are due to poor binding of features in the first place (i.e. preceding grouping and the activation of stored knowledge). Prinzmetal (1981), for instance, found that participants tended to report illusory conjunctions of two visual elements more often if the elements were both members of a perceptual group than if they were members of different perceptual groups. Prinzmetal (1981) manipulated grouping by varying the spacing between similar elements, suggesting that illusory conjunctions were modulated by bottom-up grouping factors. Subsequent researchers have found illusory conjunctions affected by factors such as the syllabic structure or cluster frequency of letters in words (Prinzmetal, Treiman & Rho, 1986; Seidenberg, 1987), consistent with a modulatory effect of stored knowledge.

Neuropsychological evidence on pre-attentive binding comes from the study of 'visual extinction'. 'Extinction' is said to occur when a patient can detect and/or identify a single stimulus presented contralateral to a site of lesion, but fails to detect/identify the same stimulus when another item is presented simultaneously in the ipsilesional field. For such patients, the ipsilesional stimulus appears to 'extinguish' the contralesional one (e.g. see Karnath, 1988). Interestingly, extinction can be affected by grouping between the items in the ipsi- and contralesional fields. When the items group, patients can sometimes identify the contralesional item — though they may fail even to detect its presence when the items do not group (e.g. see Ward, Goodrich & Driver, 1994; Gilchrist, Humphreys & Riddoch, 1996; Mattingley, Davis & Driver, 1997). This suggests that visual elements may enter into grouping prior to their being available for conscious report. In a study with the patient reported here, Humphreys, Romani, Olson, Riddoch and Duncan (1994) further demonstrated that the probability of detecting one of two stimuli was determined by how well the elements in the stimuli grouped; a stimulus whose parts grouped strongly tended to be detected in preference to a competing stimulus whose parts did not group.

### 1.1.3. Synchronised neural firing

An alternative account, which may offer some explanation of this evidence on parallel binding and on effects of grouping and stored knowledge on illusory conjunctions, is that binding is contingent on synchronised neural activity. Physiological studies have shown that there can be stimulus-dependent synchrony of firing between neurones in widely separated brain areas (e.g. Singer & Gray, 1995; Gray, Konig, Engel, & Singer, 1989). Thus neurones responding to bars that are collinear and move together will fire in a time-locked manner, whereas neural firing is not synchronised if the bars move in an uncorrelated manner. Consequently, a number of theorists have proposed that binding is based on cells that fire in synchrony (e.g. von der Malsburg, 1981; Singer & Gray, 1995), and temporal synchrony may be imposed by connections between cells that respond to elements that co-occur in perceptual groups (see Hummel & Biederman, 1992; Mozer, Zemel, Behrmann & Williams, 1992, for simulations). Such connections may enable coalitions of features to be bound rapidly and in a spatially parallel manner, though attention may subsequently be needed in order to form stable representations based on such coalitions. Hence illusory conjunctions might still occur when there is a perceptual load, though grouping and stored knowledge will constrain report. To date the majority of evidence favouring the temporal synchrony account has been physiological in nature, though some psychological evidence has been reported on the consequence of synchronised visual presentation for grouping (e.g. see Fahle, 1993; Elliott & Müller, 1998).

The arguments derived from FIT and the temporal synchrony accounts have typically not distinguished between different forms of visual binding. For FIT, there is a single process of binding via attention to a location, and this links together both form elements into shapes and the shapes with their surface properties (e.g. their colour). Similarly binding via temporal synchrony could operate similarly (and simultaneously) between elements making up visual forms and between forms and surface elements. Theories have typically not distinguished between binding within the form dimension and binding between forms and surfaces. One exception to this is the FACADE model of early visual processing put forward by Grossberg and colleagues (e.g. Grossberg & Mingolla, 1985; Grossberg, 1992; Grossberg & Pessoa, 1998). In this model, a first process of binding operates on the elements making up visual forms. This process, completed via a 'boundary contour system' (BCS) in Grossberg's terms, is sensitive to Gestalt grouping factors such as colinearity between edges. Subsequently a 'feature contour system' (FCS) acts to fill in the surface properties of the form. In this paper we examine whether the processes involved in binding form elements into an object can be distin-

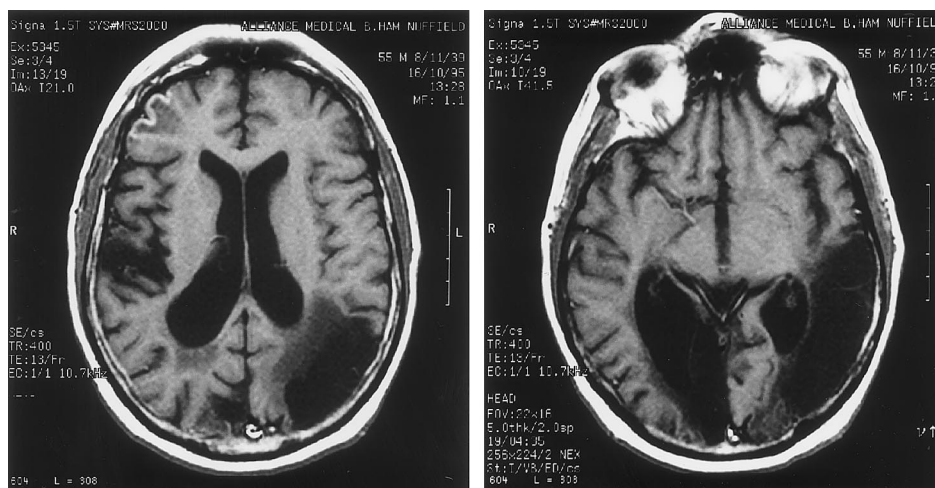


Fig. 2. MRI scan for GK.

guished from those involved in binding together form and surface details.

The paper uses neuropsychological evidence drawn from a single case study of a patient who shows both visual extinction and large numbers of illusory conjunctions in perceptual report. Due to the co-occurrence of extinction and illusory conjunctions we are able to examine whether effects of pre-attentive binding on extinction are also manifest on illusory conjunctions. If form and surface elements are bound in a single step, then common effects of pre-attentive binding should occur and this should be true whether we assess illusory conjunctions between form elements or illusory conjunctions between form and surface elements (such as colour). We report ten experiments, organised in two main sections. First we report experiments that contrast effects of grouping on extinction with grouping effects on illusory conjunctions (both within the form domain and between forms and colours). Our data show effects of grouping on extinction and on illusory conjunctions with form elements, but not on illusory conjunctions of form and colour. Subsequently we report data from studies examining the effects of the hemifield of presentation, which show that illusory conjunctions of colour and form are unaffected by whether or not stimuli occur in the same hemifield, whilst effects of grouping on extinction are greater when items fall in the same field. We discuss the results in terms of a two-stage account of the binding process.

## 2. Case report

The patient, GK (date of birth: 8 January 1939), suffered two strokes in 1986 resulting in bilateral lesions affecting the right occipito-parietal region, the right temporo-parietal region and the left temporo pari-

etal region. An MRI scan is presented in Fig. 2. Subsequent to the strokes, GK has a number of neuropsychological problems. Most notably, he suffers from Balint's syndrome, with symptoms of both optic ataxia (misreaching to visual targets) and simultanagnosia (poor report of multiple items). For example, in tests of reaching GK is able to point to parts of his own body but makes location errors when pointing to the same parts of an examiner (optic ataxia). Standard tests of simultanagnosia include visual extinction and report of complex scenes (e.g. the 'cookie theft' picture from the Boston naming test; Kaplan, Goodglass & Weintraub, 1978). Data on extinction in GK are presented in Gilchrist et al. (1996) and Humphreys et al. (1994), and we provide further new results here. GK also shows poor interpretation of complex scenes; typically he identifies only one or two of the objects present and so has difficulty in ascertaining the semantics of the scene. GK's report of stimuli tends to show a lateral bias against stimuli presented on his left side (Gilchrist et al., 1996), and he manifests visual neglect in bisection (bisecting lines to the right of their true centre). GK's reading shows aspects of both neglect (sometimes misidentifying the left-most letters in words) and attentional dyslexia (he can read words whilst being very impaired at identifying their component letters; see Hall, Humphreys & Cooper, submitted). Despite these impairments, GK functions at a high-level. He has intact memory and comprehension, is able to dress himself and to negotiate public transport alone. He does have a slight impairment in word finding which has improved in the time since the strokes. His visual deficits, however, have remained stable. Data for this paper were collected over a period between 1994 and 1999; there was no change in GK's performance either qualitatively or quantitatively (in terms of the stimulus durations used) during this period.

Table 1  
Mean correct RTs (ms), percentage errors (in brackets) and slopes of the RT-display size search functions (ms/item, underlined) for GK and age-matched controls

| Target  | Present   |           |           |       | Absent    |           |           |       |
|---|-----------|-----------|-----------|-------|-----------|-----------|-----------|-------|
|   | 1         | 3         | 5         | Slope | 1         | 3         | 5         | Slope |
| <i>(a) Colour target (red versus green)</i>                         |           |           |           |       |           |           |           |       |
| GK  | 1062 (0)  | 1183 (0)  | 1249 (0)  | 22    | 2338 (0)  | 2064 (0)  | 1834 (0)  | –57   |
| Controls  | 788 (0.5) | 813 (0.2) | 821 (0.2) | 3.6   | 865 (0.3) | 887 (0.2) | 892 (0.2) | 2.9   |
| <i>(b) Shape target (X versus O)</i>                                |           |           |           |       |           |           |           |       |
| GK  | 1046 (0)  | 1102 (0)  | 1262 (0)  | 24    | 2130 (0)  | 2495 (0)  | 2691 (0)  | 65    |
| Controls  | 812 (0.5) | 843 (0.5) | 885 (0.8) | 8.1   | 854 (0.4) | 861 (0.5) | 946 (0.5) | 10.5  |
| <i>(c) Colour-form conjunction (red X versus green X and red O)</i> |           |           |           |       |           |           |           |       |
| GK  | 1304 (0)  | 2914 (30) | 3263 (60) | 91    | 3615 (0)  | 4280 (0)  | 4360 (10) | 236   |
| Controls  | 812 (0)   | 947 (2)   | 1022 (4)  | 23    | 834 (0.5) | 1052 (2)  | 1273 (2)  | 49    |
| <i>(d) Form conjunction (T versus L)</i>                            |           |           |           |       |           |           |           |       |
| GK  | 2207 (0)  | 2699 (40) | 4410 (70) | 233   | 4201 (0)  | 4880 (10) | 4883 (10) | 85    |
| Controls  | 834 (0.4) | 960 (3)   | 1092 (5)  | 40    | 869 (0.4) | 1072 (2)  | 1476 (2)  | 68    |

### 2.1. Background results

Previous studies of patients with simultanagnosia have demonstrated impairments in conjunction search along with relatively better detection of the component features making up the conjunction stimuli (Humphreys & Price, 1994; Friedman-Hill et al., 1995). Poor conjunction search is predicted by FIT for any patient with impaired visual binding. Accordingly we first provide background data on GK's visual search abilities, contrasting search for form and colour features with search for conjunctions of form features and for colour-form conjunctions. In all of these preliminary experiments GK was presented with displays containing one, five or ten items, using a Macintosh quadra and the VSearch program. Items were presented at random locations within a display area of 12° horizontal by 10° vertical (viewed from about 60 cm). A trial began with a central fixation cross and GK reported when he was fixated on the cross<sup>1</sup>. In order to verify that GK was following this instruction we re-ran the study but with an experimenter monitoring his eyes from behind the screen. At the onset of the displays an auditory beep was presented, enabling the experimenter to judge whether an eye movement preceded the display. There was no evidence of GK making eye movements prior to the onset of displays; in fact his eye movements are typically sluggish and unlikely to play a major role in the current studies (see also Experiment 9b). Once fixated, the display was exposed for an unlimited duration. GK made a verbal yes–no response (for target present or absent trials), and the response was keyed

into the computer by the experimenter who was blind to the display. Though this can introduce some timing errors into responses, GK found it extremely difficult to make keypress responses himself; given the length of the reaction times (RTs) recorded, any timing errors can be considered negligible. GK performed four search tasks: (i) search for a red O amongst green Os; (ii) search for a red O amongst red Xs; (iii) search for a red O amongst red Xs and green Os; (iv) search for a T amongst upright and inverted Ls. (i) and (ii) can be considered feature search conditions; (iii) is a colour-form conjunction search task and (iv) can be considered a form-conjunction search task (cf. Beck, 1966; Horowitz & Wolfe, 1998). The letters were drawn in Times font, size 18. There were 30 trials at each display size, for both present and absent response (180 trials per task). The trials were randomised for each task.

The mean correct RTs (ms) and percentage errors are given in Table 1. In general GK was slow to respond. Nevertheless his responses were considerably faster, less affected by the display size and more accurate in the feature search conditions (i and ii), than in the conjunction searches (iii and iv). Indeed for the colour search condition (i), there was a negative slope on the search functions for absent trials, suggesting some sensitivity to wholistic properties of the displays. Slopes on present trials for the colour and form feature tasks were, respectively, 22 and 24 ms/item (i and ii), whereas they were 91 and 233 ms/item for the colour-form conjunction and the form conjunctions tasks (iii and iv). Moreover in the conjunction tasks high numbers of errors were made at the largest display sizes, and summing across present and absent trials performance did not differ from chance

<sup>1</sup> This procedure was used throughout the present study to ensure that GK was fixated at the start of each trial.

Table 2

|   | Correct   | One correct, one feature error <sup>a</sup> | Zero correct | Feature exchange (illusory conjunction) <sup>b</sup> | One correct only (extinction) |
|---|-----------|---|--------------|--|-------------------------------|
| <i>(a) Number (and percentage) of completely correct responses and types of error produced by GK in Experiment 2 (separated shapes)</i> |           |   |              |  |                               |
| Two items ( <i>N</i> = 144)   | 60 (41.7) | 15 (10.4)                                   | 0 (0)        | 21 (14.6)  | 48 (33.3)                     |
| one item ( <i>N</i> = 96)   | 89 (92.7) | n/a   | 3 (3.1)      | n/a  | n/a                           |
| <i>(b) Performance on two item trials as a function of the relative sizes of the shapes</i>   |           |   |              |  |                               |
| Same size ( <i>N</i> = 48)  | 18 (37.5) | 5 (10.4)                                    | 0 (0)        | 8 (16.7)   | 17 (35.4)                     |
| Small difference ( <i>N</i> = 64)   | 25 (39.1) | 7 (10.9)                                    | 0 (0)        | 9 (14.1)   | 23 (35.9)                     |
| Large difference ( <i>N</i> = 32)   | 17 (53.1) | 4 (12.5)                                    | 0 (0)        | 3 (9.4)  | 8 (25)                        |

<sup>a</sup> For example, red circle and green square → red circle and green circle.

<sup>b</sup> For example, red circle and green square → red square and green circle.

( $\chi^2(1) = 2.18$  and  $\chi^2 < 1.0$  for conditions iii and iv, respectively). These errors likely arise on trials where GK curtailed his search prematurely, lessening the true slopes of the search functions (particularly on absent trials). Table 2 also shows the mean performance of five age-matched control subjects. In terms of both RTs and errors, GK was clearly impaired in the conjunction search conditions. He was somewhat worse than the controls in the feature conditions too, though at least one control did show a similar slope in the form–feature condition (ii).

GK's poor performance in the conjunction search tasks is consistent with his having impaired binding of visual elements. If anything, GK found the form conjunction task (iv) more difficult than the colour-form conjunction task (iii), so there is no indication here of colour-form binding being necessarily worse than binding in the form domain. However, the deficit in the conjunction conditions could be due to poor control of serial search and scanning, rather than binding per se. The subsequent experiments examined binding directly.

### 3. Illusory conjunctions, extinction and grouping

In Section 3, we report eight experiments that examine the effects of grouping on both illusory conjunctions and extinction in GK. Experiment 1 provides a first test of whether illusory conjunctions do arise at an abnormal level in free report. The subsequent experiments examine grouping in more detail.

#### 3.1. Experiment 1: binding of letters and colours in free report

Experiment 1 comprised a baseline study in which we assessed whether GK would make illusory conjunctions when asked to report coloured letters from multi-item displays, even given relatively long viewing conditions.

#### 3.1.1. Method

GK received displays containing one or three letters, drawn in different colours. The target letter always fell at fixation, and the task was to report this letter and its colour. On trials with three letters, the distractor letters appeared 1° to the left and right of fixation. Stimuli were 0.5° wide × 0.8° high. In a first block of trials the targets were presented for 3 s. In a second block they were presented for 200 ms to minimise effects of eye movements. The letters and colours were drawn from sets of five values and were respectively the letters A–E and the colours red, blue, green, yellow and orange. Stimuli were presented on a Macintosh duo computer using the VScope package. In each block there were 40 trials with a single letter display and 60 with a three letter display.

#### 3.1.2. Results and discussion

With 3 s exposures GK named 38/40 of the targets presented in single letter displays, making two errors by misidentifying the letter shape; he made no colour identification errors. On three-letter trials, he named 36/60 of the target conjunctions correctly. There were five shape errors in which he misidentified the target shape as another letter not present in the display. The other 19 errors all took the form of illusory conjunction reports. With a 200 ms exposure GK identified 34/40 of the single letter displays (making six shape errors) and 29/60 of the targets in the three-letter displays (making six shape errors and 25 illusory conjunction errors). Summing across the two exposures there were 30 errors where he reported the identity of the target letter at fixation along with the colour of one of the distractor letters (on 20 trials the colour reported belonged to the distractor in his right field; on ten it belonged to the distractor in the left field); there were 14 errors which involved report of the colour of the central target letter along with the identity of one of the distractors (on 11

occasions this was the right-side distractor and on three it was the left side distractor). GK made nearly four times the number of illusory conjunction errors relative to feature identification errors, for each exposure.

Even with the relatively long viewing times used in the study, GK reported illusory conjunctions on about 32% of the trials whereas feature errors occurred on only 8% of the trials. With short exposures these figures were 42 and 10%, respectively. This rate of report of illusory conjunctions is very close to that noted by Friedman-Hill et al. (1995), in their study of a patient with Balint's syndrome. The present task is trivially easy for control subjects at both durations, and GK's performance with the three letter displays is clearly abnormal. His performance in this condition was also considerably worse than his performance with single letter displays. GK's difficulty in reporting combined colour and form information is greatly exacerbated when there are multiple items present, so that colour and form need to be bound explicitly for target report to be accurate. The results occurred even when the target was at fixation and the exposure duration minimised the opportunity for GK to make an eye movement during the trial.

### 3.2. Experiment 2: illusory conjunctions and extinction with separate coloured shapes

Experiments 2 and 3 examined perceptual report with coloured shapes. In Experiment 2 GK was presented with spatially separated shapes. In Experiment 3 the same shapes were presented but with one inside

the other, so that the shapes may group by common enclosure (see Treisman, Kahneman & Burkell, 1983; Fuentes, Humphreys, Agis, Carmona & Catena, 1998, for evidence with normal participants, and Humphreys, 1998, for neuropsychological data). In both studies, the relative sizes of the shapes were varied, to assess whether relative size information had any impact on both overall report and on the likelihood of illusory conjunctions occurring.

#### 3.2.1. Method

GK received 144 trials with two-item displays and 96 trials with single shape displays. The shapes were squares and circles, which were either 0.5, 1 or 2 in. in width and height. The shapes appeared either side of a central fixation cross, with their nearest edge 0.2 in. from fixation. The shapes were either red or green. On two-item displays, the stimuli always had different shapes and were presented in different colours. There were 16 trials for each shape pairing, for each combination of shape position and relative size. Accordingly there were 48 trials with same size shapes (16 × 0.5, 1 or 2 in.), 64 with a small size difference between the shapes (16 × sizes and positions 0.5 and 1; 1 and 0.5; 1 and 2; and 2 and 1), and 32 with a large size difference (16 × the size and position combinations 0.5 and 2; and 2 and 0.5). Each shape was red on half the trials and green on the other half, for each shape × size × position combination. In the single shape conditions, each shape appeared 12 times at each spatial position and at each size. Stimuli were presented in powerpoint on a Macintosh quadra, and displays appeared for 2 s from a viewing distance of about 60 cm. The one and two-item trials, and the different shape and colour combinations were presented randomly. GK was asked to report each shape and colour combination. Example displays are shown in Fig. 3a.

#### 3.2.2. Results and discussion

The number of correct reports, and the number of each type of error, for one and two-item displays are presented in Table 2a. GK was more accurate with one than with two-item displays (considering only responses that were completely correct;  $\chi^2(1) = 61.6$ ,  $P < 0.001$ ). There was no effect of visual field on one-item trials (left field = 43/48 (90%), right field = 45/48 (94%) correct). With two-item displays he made illusory conjunction reports. These involved complete feature exchanges between stimuli, where he miscombined the shapes with their colours; this occurred on 14.6% of all response trials and on 25% of the error trials (e.g. reporting a red square and a green circle as a red circle and a green square). He made errors where he reported one shape/colour combination correctly and the other incorrectly on 10.4% of all re-

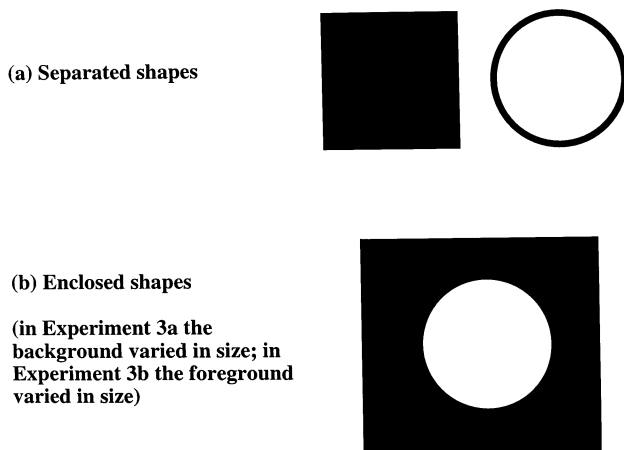


Fig. 3. Example displays from Experiments 2 and 3. (a) Example stimuli from Experiment 2. The shape and colours of the stimuli always differed (red or green, in the displays); the sizes could also vary across trials (see the text for details). (b) Example stimuli from Experiments 3a and b. In Experiment 3a the size of the background stimulus varied across trials; the size of the foreground shape was constant. In Experiment 3b the size of the foreground stimulus varied across trials; the size of the background stimulus was constant.

Table 3

|  | Correct   | One correct, one feature error <sup>a</sup> | Zero correct | Feature exchange (illusory conjunction) <sup>b</sup> | One correct only (extinction) |
|--|-----------|---|--------------|--|-------------------------------|
| <i>(a) Number (and percentage) of completely correct and types of error produced by GK in Experiment 3a (shapes grouped by common enclosure)</i> |           |   |              |  |                               |
| Two items ( $N = 64$ )   | 26 (40.6) | 15 (23.4)                                   | 0 (0)        | 11 (17.2)  | 12 (18.8)                     |
| One item ( $N = 80$ )  | 65 (81.2) | n/a   | 15 (18.8)    | n/a  | n/a                           |
| <i>(b) Performance on two item trials as a function of the relative sizes of the shapes<sup>c</sup></i>  |           |   |              |  |                               |
| Large  | 5 (31.3)  | 4 (25)                                      | 0 (0)        | 4 (25)   | 3 (18.7)                      |
| Medium   | 7 (43.7)  | 5 (31.3)                                    | 0 (0)        | 0 (0)  | 4 (25)                        |
| Medium/small   | 8 (50)    | 2 (12.5)                                    | 0 (0)        | 4 (25)   | 2 (12.5)                      |
| Small  | 6 (37.5)  | 4 (25)                                      | 0 (0)        | 3 (18.7)   | 3 (18.7)                      |

<sup>a</sup> For example, red circle and green square → red circle and green circle.

<sup>b</sup> For example, red circle and green square → red square and green circle.

<sup>c</sup>  $N = 16$  for each shape size.

sponse trials (e.g. red square and green circle → red square and red circle). Although GK was told that the latter type of trial did not occur in the study, he continued to report it as he felt it reflected ‘what he had seen’. The rate of feature-exchange illusory conjunction errors that could arise due to incorrect feature identifications can be estimated from the joint probability of two feature identification errors arising on a trial. About 1.6 feature-exchange illusory conjunctions would be expected to occur on this basis, much less than the number observed. The other main error made by GK were omissions on two-item trials; he reported one object (often correctly) but failed to report the other item. On such ‘extinction’ trials, he reported that only one item had been presented. The item omitted always fell in the left visual field.

Table 2b gives the number of errors as a function of the relative sizes of the two stimuli, on two-item trials. The number of ‘feature exchange’ illusory conjunctions due to feature misidentifications can be estimated as 0.5, 0.8 and 0.3 for the trials where shapes had, respectively: (i) the same size; (ii) a small size difference; or (iii) a large size difference (using the trials on which GK named one item correct and the other incorrectly as the baseline). Relative to these estimated levels, there was no increase in observed relative to predicted illusory conjunctions as a function of the relative sizes of the items ( $\chi^2(2) < 1.0$ ). Performance was unaffected by whether the shapes had the same size, though in each case illusory conjunctions were higher than the level predicted from feature misidentifications.

These data suggest that illusory conjunctions occurred in tasks requiring the identification of coloured shapes, as well as in letter identification tasks (Experiment 1). In addition to this, extinction errors were found.

### 3.3. Experiment 3: illusory conjunctions and extinction with enclosed shapes

There were two sub-experiments, both of which used stimuli in which one shape was enclosed within the other. In Experiment 3a, the size of the central shape was kept constant and the size of the ‘background’ shape was varied. In Experiment 3b the size of the background shape was maintained and the size of the ‘foreground’ shape was varied (see Fig. 3b). The task again required GK to report each shape along with its colour.

#### 3.3.1. Method

For Experiment 3a, the central shape was 0.5 in. and the background shape was either 0.6, 1, 2 or 4 in. in diameter. The central shape was either a square or circle, it was either red or green, and it appeared with a particular size background, on four trials per shape–colour–size combination (i.e. there were 16 trials for each background size). In Experiment 3b the outside shape was always 0.6 in. in diameter and the central shape was either 0.3, 0.2 or 0.1 in. in diameter. In Experiment 3a there were 64 two-item trials (16 for each background size); in Experiment 3b there were again 64 two-item trials but the medium sized foreground was presented for 32 trials and the other two foreground sizes for 16 trials each. In both experiments there were 80 one-item trials. The stimuli were centred at fixation.

#### 3.3.2. Results

Table 3a gives the number of correct reports and error types overall in Experiment 3a, and Table 3b gives performance broken down as a function of the size of the background shape. Table 4a presents the number of correct reports and errors in Experiment 3b, and performance is shown relative to the size of the foreground shape in Table 4b.



Table 4

|  | Correct   | One correct, one feature error <sup>a</sup> | Zero correct | Feature exchange (illusory conjunction) <sup>b</sup> | One correct only (extinction) |
|--|-----------|---|--------------|--|-------------------------------|
| <i>(a) Number (and percentage) of completely correct responses and types of error produced by GK in Experiment 3b (shapes grouped by common enclosure)</i> |           |   |              |  |                               |
| Two items ( $N = 64$ )   | 25 (39.1) | 15 (23.4)                                   | 0 (0)        | 11 (17.2)  | 13 (20.3)                     |
| One item ( $N = 80$ )  | 66 (82.5) | n/a   | 14 (17.5)    | n/a  | n/a                           |
| <i>(b) Performance on two item trials as a function of the relative sizes of the shapes</i>  |           |   |              |  |                               |
| Large ( $N = 16$ )   | 5 (31.3)  | 5 (31.3)                                    | 0 (0)        | 2 (12.5)   | 4 (25)                        |
| Medium ( $N = 32$ )  | 12 (37.5) | 7 (21.9)                                    | 0 (0)        | 6 (18.8)   | 7 (21.8)                      |
| Small ( $N = 16$ )   | 8 (50)    | 3 (18.8)                                    | 0 (0)        | 3 (18.8)   | 2 (12.5)                      |

<sup>a</sup> For example, red circle and green square → red circle and green circle.

<sup>b</sup> For example, red circle and green square → red square and green circle.

### 3.3.3. Experiment 3a

There was a significant advantage for letter reports on one-item relative to two-item trials ( $\chi^2(1) = 7.31$ ,  $P < 0.01$ ). There were 11 illusory conjunction errors involving complete feature-exchanges between the coloured shapes present (on 17.2% of all trials). The number of these errors due to feature misidentifications was 3.5 (estimated from the errors on which one object was correct and there was a feature error on the other). There were few differences between the illusory conjunction errors generated as a function of the size of the background. Performance was analysed by summing together trials with backgrounds of 1 and 2 in., to generate reasonable numbers of data points per cell. The feature-exchange illusory conjunctions expected by chance were 1, 2.1 and 1 for the large (4 in.), medium (1 and 2 in.) and small backgrounds (0.6 in.). The number of observed relative to estimated illusory conjunctions did not differ across the background sizes ( $\chi^2 < 1.0$ ). On two-item trials report of the centre coloured shape tended to be better than report of the outside coloured shape, when only two item was reported completely correctly (on 16/27 of the trials; on the remaining 13 trials only the outside coloured shape was reported correctly).

### 3.3.4. Experiment 3b

Performance with one-item displays was better than with two-item displays ( $\chi^2(1) = 27.01$ ,  $P < 0.001$ ). There were again 11 illusory conjunction errors involving complete feature exchanges (17.2% of all trials), relative to 3.5 expected by two feature misidentifications occurring concurrently, by chance. Broken down by the size of the foreground shape, chance feature exchange illusory conjunctions are predicted to be 1.6, 1.5 and 0.56 respectively (for foregrounds size 0.3, 0.2 and 0.1). There was no effect of foreground size on the likelihood of illusory conjunctions occurring, relative to the chance levels predicted from the feature misidenti-

fication error rate ( $\chi^2 < 1.0$ ). When only one coloured shape was reported correctly and two items were present, report again tended to favour the inside rather than outside stimulus (16 vs. 10/26).

### 3.4. Experiment 2 versus Experiments 3a and b

In Experiments 3a and 3b, the shapes could group from common enclosure. Consistent with there being a positive effect of grouping on extinction, there were fewer omission errors in Experiments 3a and 3b compared with Experiment 2 ( $\chi^2(2) = 9.88$ ,  $P < 0.01$ ). There was no difference in omission rates across Experiments 3a and 3b ( $\chi^2 < 1.0$ ). However, there was no difference across the experiments in the number of feature-exchange illusory conjunction responses found, relative to the numbers predicted from the rates of feature misidentification ( $\chi^2(2) = 3.17$ ,  $P > 0.05$ ). If anything, the rates of illusory conjunction responses were higher in Experiment 2 (with separated items) than in Experiments 3a and 3b (with grouped items).

#### 3.4.1. Discussion

Across Experiments 2 and 3, the number of feature-exchange illusory conjunctions was about 4.6 times the rate expected from feature misidentifications. These illusory conjunction responses were unaffected both the relative sizes of the foreground and background shapes (in Experiment 3), and by the whether the shapes were presented at separate locations (in Experiment 2) or spatially overlapping so that one shape appeared inside the other (Experiment 3). Nevertheless, there were more omission errors with separated than with overlapping shapes. Extinction was more likely in the former circumstance. There may be a number of reasons for this. One is that, in the overlapping conditions (Experiment 3), the two shapes grouped by common enclosure, so that GK tended to select both shapes together. Another is that, in Experiment 3 but not Experiment 2, the

shapes were centred at fixation. GK may be better able to select both shapes under this circumstance. We suggest that grouping was more critical than spatial location here. In other studies we have compared his identification performance with two separated shapes (as in Experiment 2) relative to performance with two shapes centred at fixation but with one partially occluding the other (giving the appearance of two shapes separated in depth rather than being grouped together; see Fig. 4 for an example). GK was no better at identifying both members of an occluding/occluded pair than he was at identifying both members of a separated pair (12/48 vs. 8/48;  $\chi^2(1) < 1.0$ ). With both separate and occluding/occluded displays performance was worse than with single item displays (45/48 in the left field and 48/48 in the right). In this case, having two items centred at fixation did not benefit performance and, with both separated and occluding/occluded stimuli, relatively large numbers of omissions occurred (on 20/48 trials with separate shapes and on 24/48 trials with occluding/occluded shapes). Interestingly with the occluding central shape, these omissions all involved GK identifying the background stimulus — apparently because it had a part falling further into his right field (see also Experiment 10 here). Presenting stimuli at fixation was no guarantee that they would be better reported (see also Humphreys et al., 1994, and Experiment 1). We conclude that the reduced omissions in Experiment 3 relative to Experiment 2 was due to grouping by common enclosure in Experiment 3. Whichever the case, there was no effect on the proportion of illusory conjunction errors relative to the errors expected by chance feature misidentifications.

Experiment 4 tested the effects of grouping further, using stimuli that grouped on the basis of various properties: contrast polarity, shape, collinearity and connectedness. Gilchrist, Humphreys, Riddoch and Neumann (1997) demonstrated effects of grouping by contrast polarity, common shape and collinearity under conditions of apparently parallel search in normal

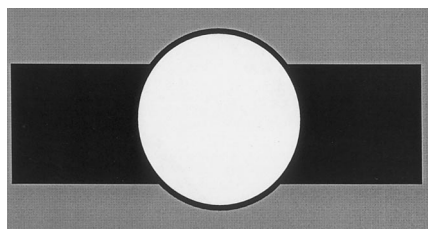


Fig. 4. Example of the occluding stimuli used in further studies with GK. The central stimulus appeared at fixation. The task was to report the colour and shape of both items. The stimuli were shown in black and white against a grey background.

subjects, suggesting that grouping based on these factors operated pre-attentively. Qualitatively similar effects on extinction in GK were reported by Gilchrist et al. (1996). They presented either pairs of squares (having collinear edges), pairs of circles (lacking collinear edges but having common shape), or squares and circles. In addition, the members of a pair could either have the same or opposite contrast polarities (e.g. both white or one white and one black, against a grey background). Extinction was greatest when the stimuli differed both in shape and contrast polarity (e.g. a black square and a white circle), and it occurred on fewest trials when the shapes were the same, had the same contrast polarity and had collinear edges (e.g. two white squares). In addition to these factors, grouping should also operate between connected elements (see Palmer & Rock, 1994; see Humphreys & Riddoch, 1993, for prior evidence on simultanagnosia, and Driver, 1998, for evidence from patients showing unilateral extinction). Note that although the strength of grouping should vary as contrast polarity, shape similarity, collinearity and connectedness vary, the positions of the shapes in the field can stay constant. Here effects of grouping can be clearly distinguished from those due to field position.

### 3.5. Experiment 4: effects of contrast polarity, shape similarity, collinearity and connectedness

GK was presented with displays containing either single squares or circles in his left or right fields, or two-item displays derived from the various pairings of the shapes and field positions. The shapes were either white or black and they appeared against a grey background. Shape pairs, when present, could also be joined by a connecting black line (on the one- and two-item trials where the line did not connect the shapes, it remained present but fell short of either the left or the right shape; see Driver, 1998). The task was to identify the shapes and their colours (black or white). Example displays are presented in Fig. 5.

#### 3.5.1. Method

The stimuli were squares and circles 0.5 in. across. Stimuli were presented with their centres 0.5 in. from fixation. There were 108 trials with a single stimulus presented in the left field and 108 single right stimulus trials (27 trials for each shape and colour). There were 144 trials each when there two separated and two connected stimuli; 72 trials with the same-shape stimuli (18 same colour and 18 different colour, for both two square and two circle trials) and 72 with different shape stimuli (36 same colour, 36 different colour), for both the joined and the separated conditions. When the stimuli were the same colours they were both black or

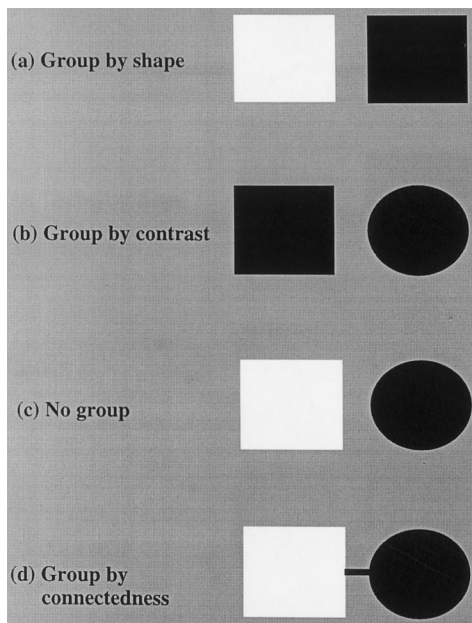


Fig. 5. Example stimuli from Experiment 4. When there were two stimuli present, they could (a) group by common shape; (b) group by common contrast; (c) not group (differing in shape and contrast polarity); and (d) group by connectedness. Stimuli were presented in black and white against a grey background.

both white on half the trials; when they were different colours the left item was white and the right item black, or vice versa, on half the trials. When the two shapes were connected there was a black line, 0.5 in. long, that fell through fixation joining the two shapes. On all other trials the same black line appeared but it was only 0.125 in. long and it did not connect onto any of the shapes. Items were presented for 1 s against a mid-grey background. The experiment was also run with seven age-matched control subjects, to assess whether grouping affected the rate of illusory conjunctions for them. The conditions matched those used for GK except that stimuli were presented for 200 ms and they were followed by a pattern mask containing all of the possible stimuli shown in the study, at randomly positioned locations.

### 3.5.2. Results and discussion

GK identified single left stimuli on 94/108 trials (87% correct) and single right stimuli on 97/108 trials (90% correct). There was no effect of visual field ( $\chi^2 < 1.0$ ). He identified the shapes and colours of both items on 29/144 of the trials with separated stimuli (20% correct) and on 58/144 of the trials with connected stimuli (54% correct). Performance was better with connected than with separated items ( $\chi^2(1) = 12.91$ ,  $P < 0.01$ ), though even with connected stimuli performance was worse than when single items

were presented to the left field ( $\chi^2(1) = 51.16$ ,  $P < 0.001$ ).

Table 5a gives the scores on the two-item trials broken down as a function of the shapes, their contrast polarities and whether or not they were connected. The results with separated items essentially replicate those reported by Gilchrist et al. (1996), but using an identification rather than a detection procedure. Identification was best for two squares, followed by the two circle stimuli, and it was worst for pairs of different shapes; performance was also better when items had the same contrast polarity relative to when they had different contrast polarities; contrast polarity, shape similarity (with circles) and collinearity (with squares) combined in a generally additive manner. Overall there were reliable effects of contrast polarity ( $\chi^2(1) = 4.32$ ,  $P < 0.05$ ) and of shape similarity (same shapes versus different shapes;  $\chi^2(1) = 17.27$ ,  $P < 0.01$ ). With connected items there remained a significant effect of shape similarity (same versus different shapes,  $\chi^2(1) = 10.42$ ,  $P < 0.01$ ), but the effect of contrast polarity was no longer reliable ( $\chi^2 < 1.0$ ). There is some evidence here that grouping by connectedness overcame effects of grouping based on a surface property of the stimuli: contrast polarity.

In this study, illusory conjunction errors can be assessed in either of two ways. First, in the conditions in which the shapes differed in one property, the rate of illusory conjunctions can be compared with the rate of feature errors when one feature of at least one stimulus was misreported. For example, when the stimuli were a white square and a white circle, a conjunction error would be to report two white squares; a feature error would be to report a black square and a white circle (a colour feature error in this case; when the stimuli were the same shape but differed in colour, a shape feature error could arise by reporting the shape not present on that trial). Note that the opportunities for conjunction and feature errors were equated on trials where the stimuli differed by one attribute. Second, when the stimuli differed in both properties (as in Experiments 2 and 3), the rate of feature-exchange (illusory conjunction) errors could be compared with the rate of errors when just one feature was reported incorrectly.

Taking the conditions in which shapes differed in one property, there were 14 conjunction errors and four feature errors (plus 28 extinction trials). Though there were more extinction errors with separate shapes (20 vs. 8 with connected shapes), the rates of conjunction to feature errors were constant (seven conjunction to two feature errors, for both connected and separated shapes).

Table 5b presents the results for GK on two-item trials on which the shapes and contrast polarities of

Table 5

| Connectedness  | Separated |                                |              | Connected                               |                               |              |
|--|-----------|--------------------------------|--------------|---|-------------------------------|--------------|
|  | Same      | Different                      |              | Same                                    | Different                     |              |
| <i>(a) Number (and percentage) of completely correct reports of the two shapes and contrast values by GK as a function of the stimulus conditions in Experiment 4</i>        |           |                                |              |   |                               |              |
| Two squares  | 12 (66.7) | 6 (33.3)                       | 25/72 (34.7) | 14 (77.8)                               | 8 (44.4)                      | 39/72 (54.2) |
| Two circles  | 6 (33.3)  | 1 (5.6)                        | 9 (50)       | 8 (44.4)                                |                               |              |
| Square and circle  | 2 (5.6)   | 2 (5.6)                        | 4/72 (5.6)   | 8 (22.2)                                | 11 (30.6)                     | 19/72 (26.4) |
|  | Correct   | One correct, one feature error | Zero correct | Feature exchange (illusory conjunction) | One correct only (extinction) |              |
| <i>(b) Number (and percentage) of completely correct responses by GK, along with different error types with two different shapes and contrast polarities in Experiment 4</i> |           |                                |              |   |                               |              |
| Separated ( $N = 36$ )   | 2 (5.6)   | 2 (5.6)                        | 1 (5.6)      | 7 (19.4)                                | 24 (66.7)                     |              |
| Connected ( $N = 36$ )   | 11 (30.6) | 3 (8.3)                        | 0 (0)        | 10 (27.8)                               | 12 (33.3)                     |              |

the stimuli differed. There was an effect of connectedness on extinction: there were proportionately fewer extinction responses with connected than with separated items ( $\chi^2(1) = 6.72$ ,  $P < 0.01$ ). The observed rate of complete feature-exchange responses can be compared with the rate expected from baseline trials on which there was one item correct and one feature error. In the connected condition, 0.25 feature exchanges would be expected (relative to the ten observed) and in the separated condition 0.11 (relative to seven observed). There was no difference between the proportions of feature-exchange illusory conjunctions found with connected and separated items, relative to these baseline predictions ( $\chi^2 < 1.0$ ), though in each case observed feature-exchange (illusory conjunction) responses exceeded those predicted from the single feature-error baselines.

The mean correct report across the control subjects was 79% for the separated items and 88% for the connected shapes, 88% for same polarity versus 81% for different polarity and 88% for the same over 85% for different shapes. There were reliable main effects of separation and contrast polarity on report, with performance being better when the items grouped (were connected or the same polarity;  $F(1,6) = 12$  and 9, respectively, both  $P < 0.025$ ). There were no other effects on report accuracy. A count of conjunction response errors was taken from the trials when the stimuli differed by at least one attribute (white square, white circle  $\rightarrow$  2 white squares) plus the feature-exchange trials when two attributes differed (white square, black circle  $\rightarrow$  black square, white circle). These conjunction errors were compared with an expected rate estimated from (i) feature errors from the trials on which the stimuli differed by one attribute (white square, white circle  $\rightarrow$  black square, white circle) plus (ii) the expected

rate of feature exchanges taken from single feature error trials when two attributes differed (white square, black circle  $\rightarrow$  black square, black circle). There was a reliable overall effect of connectivity ( $F(1,6) = 6.45$ ,  $P < 0.05$ ); there were more errors to separate relative to connected shapes. In addition this factor interacted with the contrast between observed and expected conjunction errors ( $F(1,6) = 6.67$ ,  $P < 0.05$ ). There were more observed than expected conjunction errors when the shapes were connected relative to when they were separate; indeed, there was no increase in observed over expected conjunction errors for separate shapes. The mean proportions of trials for observed and expected conjunction errors are given in Table 6.

The data from the controls confirm that grouping aids stimulus report, and also that conjunction errors of shape and contrast polarity were affected by grouping. When the shapes were connected the level of conjunction errors was greater than predicted by the level of feature errors; this was not the case when the shapes were separate. The failure to find reliable numbers of conjunction errors with separate shapes may reflect either that there is relatively low power of the test with just seven subjects, or that the controls experienced relatively severe data limitations with these items, which proportionately increased feature errors. We report a similar effect of data limitation for GK in Experiment 9b.

Table 6  
Percentage illusory conjunction and feature errors reported by control subjects (Experiment 4)

| Grouping condition | Separated   |         | Connected   |         |
|--------------------|-------------|---------|-------------|---------|
|                    | Conjunction | Feature | Conjunction | Feature |
|                    | 8.04        | 8.52    | 7.61        | 3.34    |

Table 7  
Number (and percentage) of completely correct responses by GK, along with the different errors produced, in Experiment 5 (error examples given to the stimulus: red square and green circle)

| New feature added   | Colour       | Shape        | Total        |
|---|--------------|--------------|--------------|
| Correct   | 16<br>(26.7) | 11<br>(18.3) | 27<br>(22.5) |
| <i>Error categories</i>   |              |              |              |
| (a) One correct and one shape repetition<br>(Red square, green square)            | 11<br>(18.3) | 7<br>(11.7)  | 18<br>(15)   |
| (b) One correct and one colour repetition<br>(Red square, red circle)             | 1<br>(1.7)   | 0<br>(0)     | 1<br>(0.8)   |
| (c) One correct and one new feature error<br>(Red square, blue circle)            | 4<br>(6.7)   | 9<br>(15)    | 13<br>(10.8) |
| (d) One feature exchange and one new feature<br>Error (green square, blue circle) | 5<br>(8.3)   | 3<br>(5)     | 8<br>(6.7)   |
| (e) One object only (extinction)<br>(Red square)                                  | 9<br>(15)    | 23<br>(38.3) | 32<br>(26.7) |
| (f) One feature exchange<br>(Red circle)  | 4<br>(6.7)   | 2<br>(3.3)   | 6<br>(5)     |
| (g) Complete feature exchange<br>(Red circle, green square)                       | 6<br>(10)    | 5<br>(8.3)   | 11<br>(9.2)  |
| (h) One correct and both features incorrect<br>(Red square, blue square)          | 4<br>(6.7)   | 0<br>(0)     | 4<br>(3.3)   |
| (i) Both items incorrect<br>(Blue square, blue circle)                            | 0<br>(0)     | 0<br>(0)     | 0<br>(0)     |

For GK, grouping between shapes reduced extinction. We found effects here based on shape similarity, contrast polarity and connectedness. These results are consistent with forms of binding operating pre-attentively, prior to GK having conscious access to the information on which binding takes place. Illusory conjunction errors also occurred at a rate much higher than predicted by feature misidentifications. However, in contrast to extinction, grouping did not modulate the numbers of illusory conjunction responses; in particular, feature exchanges between stimuli differing in shape and contrast polarity were no more likely when they were connected than when they were separated. These results suggest that, for GK, illusory conjunctions can be dissociated from grouping effects on perceptual report, a point that we return to in the discussion to this section.

### 3.6. Experiment 5: illusory conjunctions versus new feature errors

In Experiments 2 and 3 we estimated the rate of illusory conjunctions due to feature misidentifications from the only feature errors that occurred in those experiments, which was when GK identified one item

correctly and the second stimulus incorrectly — typically reporting a feature repetition (e.g. red square and green circle → red square and red circle). However it is possible that these repetition errors are themselves illusory conjunctions and not feature misidentifications at all. Hence, although we have consistently found that illusory conjunctions involving complete feature exchanges were three times or more frequent than predicted from the repetition error baselines, we may actually be underestimating the number of ‘true’ illusory conjunctions. One standard way to estimate the number of illusory conjunctions that can be expected by chance is to incorporate a ‘new’ feature error baseline (e.g. Treisman & Schmidt, 1982). Feature errors of this type were possible in Experiment 4, in conditions where the stimuli differed by one attribute (white square, white circle → black square, white circle), but not when the stimuli differed by two attributes (where any misreport could be a conjunction error and not just a feature misidentification). Hence we may still be underestimating illusory conjunctions on trials with stimuli differing in both shape and surface property. To provide a proper estimate on these trials, experiments need to employ at least three feature types across trials, though only two may be present on a given trial. The number of errors made by reporting the third feature, not actually present, can then be used to estimate the true level of feature misidentifications, uncontaminated by the items present in the field. This was done in Experiment 5, where we extended the shape identification studies to incorporate new feature baselines in a task requiring the identification of coloured shapes. In one block of trials GK was presented with square and circle shapes again, but the shapes could be red, green or blue. Here we could estimate the number of colour misidentifications from feature errors involving the colour not present on a trial. In a second block of trials there could be squares, circles or triangles, which could be red or green. This block provides an estimate of shape feature errors.

#### 3.6.1. Method

There were 60 trials in each block, and these always used two spatially separated stimuli which differed in both shape and colour. The squares and circles were 0.5 in. across; the triangles were equilateral with sides 0.5 in. long. Items appeared with their nearest point 0.2 in. from fixation (as in Experiment 2). Stimuli were presented using powerpoint and appeared for 2 s per display.

#### 3.6.2. Results and discussion

The number of completely correct responses, along with the numbers of different error types, are given in Table 7. GK scored 16/60 (27%) correct in the block with three colour features and 11/60 (18%) correct in

the block with three shape features. The errors were categorised as follows (taking as an example a display containing a red square and a green circle):

- a. one object correct (colour + shape) + shape repetition error (e.g. red square, green square);
- b. one object correct + colour repetition error (red square, red circle);
- c. one object correct + new feature error (red square, blue circle);
- d. one feature exchange error + new feature error (green square, blue circle);
- e. one object only (red square);
- f. one feature exchange error only (red circle);
- g. feature exchange illusory conjunction (red circle, green square);
- h. one correct and both features of the other item incorrect (red square, blue square);
- i. both items incorrect (blue square, blue circle).

Illusory conjunctions here could lead to errors in categories a, b, d, f and g. New feature errors can be calculated by summing error categories c, d, h and i. Summing together the data from the two blocks of trials, there were 44 trials where illusory conjunctions might have arisen and 25 trials where new feature errors occurred. Taking this total number of new feature error trials, we can estimate the number of trials on which two feature errors could occur by chance; this was 5.2. The number of complete feature exchanges was double this, 11. The results remain consistent with illusory conjunctions occurring even under the long presentations conditions of the study and even when illusory conjunctions are estimated from the level of new feature errors in coloured shape identification.

### 3.7. Experiment 6: forced choice identification

It is possible that illusory conjunctions arise in memory rather than in visual perception, especially when illusory conjunctions are measured in a patient such as GK, who can take quite a long time to report stimuli. For example, GK might encode that there was a red shape present, but then forgets whether this shape was the square or the triangle. However, there are reasons to doubt this interpretation for the present study. First GK tended to produce high numbers of complete feature exchange errors which affected the initial item reported as well as the item reported subsequently; illusory conjunctions in memory are more likely to arise for items reported later in time. Second, GK insisted on reporting feature repetition errors even though he was told that these were not possible in the studies. He insisted on making such errors because he felt that these were the items that he had seen. This suggests that GK was reporting his perceptions. Nevertheless, to provide a stronger evaluation of whether the illusory conjunctions were perceptual in nature, we used a

forced-choice identification procedure in Experiment 6. In Experiment 6a, GK received separated coloured shapes, as in Experiment 2; in Experiment 6b he received shapes grouped by common enclosure (as in Experiment 3). In both sub-experiments the task was to detect the presence of a red circle. On target present trials, one item was the target and the second stimulus, when present, differed in both shape and colour. On target absent trials, the stimuli fell into four categories: (a) the target features were present but in the two distractors (e.g. distractors: red square and yellow circle) (illusory conjunction false alarms); (b) the shape feature was present but the colour feature was absent (distractors: blue square and yellow circle) (colour intrusion error); (c) the colour feature was present but the shape feature was absent (distractors: red square and green triangle) (shape intrusion error); (d) both target features were absent (distractors: blue square, yellow triangle) (colour and shape feature errors). On trials where GK missed a target, he was always asked to identify what he saw, since it is possible to miss a target due to illusory conjunctions being formed between the features of the target and those of the distractor present. If illusory conjunctions are perceptual in nature then: (i) illusory conjunctions will be reported when GK misses targets, and (ii) he may make false alarms (when targets are absent) in condition (a).

#### 3.7.1. Experiment 6a: separated stimuli

**3.7.1.1. Method.** To provide a thorough estimate of illusory conjunctions, GK was tested over 16 blocks of trials: eight with a short stimulus durations (150 ms), and eight with a longer duration (1 s). Stimuli were presented via the VScope package. The stimuli were centred 2.5 in. from fixation and they were 1 in. across. Non-target features were square and circle, and blue and yellow. Each block of trials contained 80 trials with two items present: 16 with the target present and 64 target absent trials (16 for each type of absent trial). In addition there were 48 single item trials, 16 with the target present and 32 with the target absent. For the one-item absent trials the distractor had the target shape on eight trials, the target colour on eight trials and neither the target colour nor shape on 16 trials. Single items appeared equally often left and right of fixation. Similarly on two item trials the target fell an equal number of trials on the right and left of fixation; on two-item absent trials distractors sharing a target feature also fell equally often left or right of fixation.

**3.7.1.2. Results and discussion.** Table 8 gives the number of correct and error responses for each condition (one or two-items, target present or absent). Errors on present trials were classified as involving an illusory conjunction if GK reported an incorrect combination

of one target attribute and one distractor attribute (red circle and blue square → red square). Colour or shape feature errors reflected report of one target feature along with a new feature error occurring (e.g. red circle and blue square → red triangle — a shape feature error); colour and shape feature errors reflected report of neither target attribute (red circle and blue square → blue triangle). The data were analysed by comparing the number of illusory conjunction errors, relative to the combined total of feature errors, with trial block treated as subjects. The factors were stimulus duration (150 ms vs. 1 s), target present or absent, and error type (illusory conjunction vs. feature error). There was a marginal effect of target present or absent ( $F(1,7) = 4.79$ ,  $P = 0.07$ ), and a significant effect of error type ( $F(1,7) = 12.91$ ,  $P < 0.01$ ). Target duration was not reliable ( $F(1,7) = 2.92$ ,  $P > 0.05$ ). There was one reliable interaction, between target present or absent and error type ( $F(1,7) = 9.62$ ,  $P < 0.02$ ). There were more illusory conjunction than feature errors on target present trials, but not on absent trials. When GK responded incorrectly that a target was absent, he tended to report an illusory conjunction involving one feature of the target and one of the distractor present on the trial, rather than any other type of feature error. In addition to this, he made a substantial number of extinction-type errors, where he typically identified the right field distractor and stated that there was only one item present, particularly with a short duration. On single item trials GK made very few errors. On single item trials GK scored 348/384 (90.6%) with 150 ms presentations and 360/384 (93.8%) on 1 s presentations.

This study demonstrates that illusory conjunction errors occurred more often than feature errors even under forced-choice conditions. In addition there were extinction errors when exposure durations were reduced. Illusory conjunctions remained at about the

same level across the two target durations. In Experiment 6b a similar procedure was applied to stimuli grouped by common enclosure.

### 3.7.2. Experiment 6b: stimuli grouped by common enclosure

**3.7.2.1. Method.** GK participated in just two blocks of trials, sufficient to test whether the data followed the same pattern as that found in Experiment 6a. Only two item trials were used, with the stimuli centred at fixation. The central (foreground) shape was always 0.5 in. at its widest point. The background shape was either 1, 4 or 7.5 in. across. The target was again a red circle, which was equally often in the foreground and the background. There were 150 trials in each block, 72 target present, six colour and shape error absent trials and 24 for each of the other absent trials (illusory conjunction false alarms, colour intrusions and shape intrusions). When GK responded incorrectly on a target present trial he was asked to report the shapes and colours present. Stimuli appeared for 2 s, and were presented via powerpoint.

**3.7.2.2. Results and discussion.** The number of correct responses and errors are presented in Table 9a. GK made few errors on absent trials, but he made 46/144 errors on present trials. On one present trial GK reported the distractor and failed to identify the target (an extinction trial); on another five trials he made a shape feature error (red circle and yellow triangle → red square). On the remaining 40 error trials he reported an illusory conjunction involving the target colour along with the shape of the distractor. Again GK reported illusory conjunctions when tested under forced choice conditions, when asked only to detect a single coloured target shape.

Table 9b presents the number of correct target detections as a function of the size of the background shape. Performance was worst when the background shape was smallest ( $\chi^2(2) = 7.62$ ,  $P < 0.05$ ). This result could arise for a number of reasons. One is that, as the size of the background shape increases so GK tends to treat it as the perceptual ground; consequently, the distractor does not compete so strongly for selection with the target shape. However we would then expect differences according to whether the target was in the foreground or the background: the detection of foreground targets should improve as the background size increases, but the detection of background targets should decrease. As Table 9b shows, though, there was no evidence for this; the same pattern of results held irrespective of whether the target was in the foreground or background. An alternative is that performance here was affected by

Table 8

Number (and percentage) of correct responses given by GK using a forced-choice target detection procedure to separate shapes: two item trials only (Experiment 6a)<sup>a</sup>

| Target                     | Present   |            | Absent     |            |
|----------------------------|-----------|------------|------------|------------|
|                            | 150 ms    | 1 s        | 150 ms     | 1 s        |
| Correct                    | 67 (52.3) | 110 (85.9) | 463 (90.4) | 453 (88.5) |
| Illusory conjunction       | 21 (16.4) | 13 (10.1)  | 21 (4.1)   | 35 (6.8)   |
| Colour intrusion           | 4 (3)     | 0 (0)      | 2 (0.4)    | 3 (0.6)    |
| Shape intrusion            | 4 (3)     | 1 (0.8)    | 24 (4.7)   | 18 (3.5)   |
| Colour and shape intrusion | 1 (0.8)   | 0 (0)      | 2 (0.4)    | 3 (0.6)    |
| Miss                       | 31 (24.2) | 4 (3.1)    | 0 (0)      | 0 (0)      |

<sup>a</sup>  $N = 128$  for present and 512 for absent, at each duration.

Table 9

| Trial type   | Present   | Absent                           |                  |                 |                            |
|--|-----------|----------------------------------|------------------|-----------------|----------------------------|
|  |           | Illusory conjunction false alarm | Colour intrusion | Shape intrusion | Colour and shape intrusion |
| <i>(a) Number (and percentage) of correct responses given by GK using a forced-choice target detection procedure to shapes grouped by common enclosure (Experiment 6b)<sup>a</sup></i> |           |                                  |                  |                 |                            |
| Correct  | 98 (68.1) | 46 (95.8)                        | 46 (95.8)        | 48 (100)        | 12 (100)                   |
| Error  | 46 (31.9) | 2 (4.2)                          | 2 (4.2)          | 0               | 0                          |
| Target position  | Inside    | Outside                          |                  |                 |                            |
| <i>(b) Number (and percentage) of correct target detection responses as a function of the position (inside/outside) and size of the background shape</i>                               |           |                                  |                  |                 |                            |
| Background shape   |           |                                  |                  |                 |                            |
| Small  | 13 (54.2) | 13 (54.2)                        |                  |                 |                            |
| Medium   | 18 (75)   | 20 (83.3)                        |                  |                 |                            |
| Large  | 16 (66.7) | 18 (75)                          |                  |                 |                            |

<sup>a</sup>  $N = 24$  per cell.

how GK allocated spatial attention in order to select the target. For example, selection may depend on some form of ‘attentional window’ being optimised to the target (see Olshausen, Andersen & Van Essen, 1993; Humphreys & Heinke, 1998, for explicit accounts). When the distractor is similar in size to the target, its attributes may sometimes be selected in place of those of the target since the attentional window fails to differentiate the stimuli. When the stimuli differ in size, the window set to the target may enable it to be selected rather than attributes of the distractor. When the target is in the foreground, a small window will enable the target to be selected preferentially, particularly as the distractor’s size increases. When the target is in the background, a large window will now favour a large target, since, within the window, there will be more evidence for the large target than for the small distractor. We note also that this is the only study where we have found evidence for effects of the relative size of targets and distractors on illusory conjunctions. Any effects due to the setting of an attentional window may be most apparent when the target location is predictable (as here, where stimuli were centred at fixation) and the task requires GK to make a forced-choice response. Under free report conditions (e.g. Experiment 3), GK may simply not report weak information when target and distractor attributes compete for selection within the attentional window that GK is able to pre-set in the task.

Direct comparisons of the number of target misses (extinction trials) across Experiments 6a and 6b are difficult to make, given the different stimulus durations used in the studies (though effects of exposure duration on Experiment 6a were not reliable). However illusory conjunctions may be measured relative to the feature

error baselines within each experiment. There were 40 illusory conjunction reports to five feature errors in Experiment 6b, compared with 34 illusory conjunction responses to ten feature errors in Experiment 6a. This increase in the proportion of illusory conjunctions to feature errors in Experiment 6b was not reliable ( $\chi^2(1) = 1.39, P > 0.05$ ).

Table 10

| Target  | Present    |            | Absent     |            |
|---|------------|------------|------------|------------|
|   | Same       | Different  | Same       | Different  |
| <i>(a) Number (and percentages) of correct responses and error types for forced-choice detection of form-contrast targets as a function of whether targets and distractors appeared in the same or different hemifields, for 1 s (Experiment 9a)<sup>a</sup></i>    |            |            |            |            |
| Correct   | 269 (84)   | 266 (83.1) | 376 (94)   | 368 (92)   |
| Error type  |            |            |            |            |
| Illusory conjunction  | 26 (10.2)  | 31 (12.1)  | 12 (3)     | 15 (3.9)   |
| Shape feature   | 8 (3.1)    | 10 (3.9)   | 12 (3.1)   | 15 (3.9)   |
| Colour feature  | 0 (0)      | 0 (0)      | 0 (0)      | 2 (0.5)    |
| Miss  | 17 (6.6)   | 13 (5.1)   |            |            |
| <i>(b) Number (and percentages) of correct responses and error types for forced-choice detection of form-contrast targets as a function of whether targets and distractors appeared in the same or different hemifields, for 200 ms (Experiment 9b)<sup>b</sup></i> |            |            |            |            |
| Correct   | 163 (48.5) | 156 (46.4) | 312 (92.9) | 307 (91.4) |
| Error type  |            |            |            |            |
| Illusory conjunction  | 22 (6.5)   | 23 (6.8)   | 14 (4.2)   | 18 (5.4)   |
| Shape feature   | 16 (4.8)   | 25 (7.4)   | 10 (3)     | 8 (2.4)    |
| Colour feature  | 0 (0)      | 0 (0)      | 0 (0)      | 3 (0.8)    |
| Miss  | 135 (40.2) | 132 (39.3) | n/a        | n/a        |

<sup>a</sup>  $N = 320$  for present and 400 for absent trials.

<sup>b</sup>  $N = 336$  for present and absent trials.



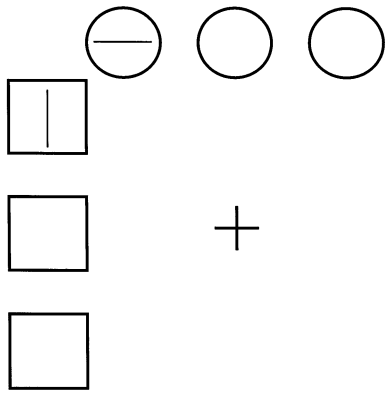


Fig. 6. Example display from Experiment 8, adapted from Pomerantz (1991). Note that the fixation cross was not presented simultaneously with the shapes but is shown here to illustrate the positions of the shapes relative to fixation. The example shows an 'absent' trial with elements which are in different groups which could form an illusory conjunction.

### 3.8. Experiment 7: sequential presentation

Problems in binding should be exacerbated under simultaneous presentation conditions, relative to when items are temporally separated and there is the opportunity to bind the parts of an object without competition from other objects. Friedman-Hill et al. (1995), for example, reported that their patient with Balint's syndrome, who made abnormally large numbers of illusory conjunction responses when multiple stimuli occurred simultaneously, made few when items appeared sequentially for the same total duration. GK's ability to bind sequentially presented visual information was tested in Experiment 7.

#### 3.8.1. Method

A forced-choice identification procedure was used, matching Experiment 6b in all respects except that items appeared sequentially, each for 1 s (so that the total stimulus duration matched the one used in Experiment 6b). GK's task was to decide whether or not a red circle was presented on a trial. A single block of 150 trials was administered.

#### 3.8.2. Results and discussion

GK scored 68/72 on target present trials and 70/72 on target absent trials. GK was reliably better at detecting the target here than he was in Experiment 6b, with simultaneous presentation of two targets ( $\chi^2(1) = 72.75, P < 0.001$ ). His errors on present trials involved one illusory conjunction report (pairing the target colour with the distractor shape), one shape error and two trials where he reported the distractor correctly but was unable to report the target (an extinction-type trial). On absent trials he made one illusory conjunction false alarm and one shape intrusion. Clearly GK was

better able to bind the colour and shape of stimuli presented consecutively for 1 s each, than he was a pair of items presented simultaneously for 2 s; consequently he made very few errors. GK's problem with binding arises when features from distractor stimuli are available at the same time as those in targets.

### 3.9. Experiment 8: illusory conjunctions of form

The evidence we have reported so far has indicated that GK makes illusory conjunction responses at a level higher than expected from feature misidentifications, that illusory conjunctions arise even under forced-choice testing conditions, and that illusory conjunctions of surface information (contrast polarity, colour) and shape are not affected by grouping between the parts of objects. In contrast, extinction is reduced when visual elements group (Experiments 3 and 4). This contrast suggests that pre-attentive binding between form elements can take place and this influences the degree of extinction that occurs, but, for GK, form-binding does not constrain the binding of surface features to form. Controls, however, do show effects of form grouping on illusory conjunctions of shape and surface property (Experiment 4). In Experiment 8 we sought to test whether GK's perceptual report of illusory conjunctions was influenced by grouping when form elements had to be identified. We adopted the procedure used by Prinzmetal (1981), which examined the discrimination of form elements presented either within a perceptual group or between perceptual groups defined by proximity and similarity of shape. Are illusory conjunctions of form more likely within relative to between perceptual groups?

#### 3.9.1. Method

A forced-choice discrimination task was used in which GK had to detect the presence of a target cross (+). Distractors were horizontal or vertical line elements (the components of the cross). Targets and distractors appeared within horizontal or vertical arrays of shapes which grouped based on average proximity and similarity of form (see Fig. 6). The horizontal arrays were always circles and the vertical arrays always squares. The distance between the nearest shapes in the vertical and horizontal groups was the same as the distance between the shapes within each group, though the average distances within the groups was greater than the distances between groups. The arrays could appear in one of four positions around fixation (vertical: left or right, horizontal: above or below), and there was always one vertical and one horizontal array on each trial. Targets and distractors always fell in either of two shapes per group, which were the ones closest to the other group (e.g. in Fig. 6, stimuli could appear in the top and middle shapes in the vertical group, and in

the left and middle shapes in the horizontal group). On one-item trials either a single target or distractor appeared in one of the four permissible arrangements of the two arrays, and in one of the four local positions within each arrangement. In a trial block there were 32 single target present trials and 32 single distractor trials. On two-item trials targets again appeared in one of the four arrangements of the arrays, and in one of the four locations per arrangement. Distractors either appeared within the same group (when it appeared in the neighbouring shape to the target) or within different groups. When the target and a distractor appeared in different groups, they could either be close (matched to the distance between items within a group), moderately spaced (e.g. target in the left-most shape in the horizontal array, distractor in the middle shape of the vertical array) or widely spaced (both in the middle positions of the arrays). The target also appeared either with a vertical or with a horizontal distractor. There were 64 trials with the target and distractor in the same group, and 64 with them in different groups (16 close, 32 moderate and 16 widely spaced). The two-item trials with no target comprised either illusory conjunction false alarms (vertical and horizontal distractors), vertical feature errors (two horizontal distractors) or horizontal feature error trials (two vertical distractors). For each of these trial types, distractors could fall in the same group or in different groups, and when in different groups they could be close, moderately spaced or widely spaced. There were 48 same-group trials for each distractor type, and 48 different group trials (16 per spacing). Altogether there were thus 480 trials. Circles and squares were 0.5 in. across and were separated from their nearest neighbours by 1 in. (within and between groups). The middle shape in each array fell 1.63 in. from fixation. Each display was presented for 2 s, using the VScope program on a Macintosh duo computer. The conditions were fully randomised. Target lines and the arrays appeared simultaneously and remained on the screen for 2 s.

### 3.9.2. Results and discussion

GK scored 100% on single item trials (32/32 present, 32/32 absent). On two-item trials he detected 95/128 (74%) of the targets correctly. There was an effect of whether targets and distractors appeared in the same or in different groups. He detected targets on 54/64 (84%) of the trials in the same group condition relative to 41/64 (64%) of the trials when they appeared in different groups ( $\chi^2(1) = 5.87$ ,  $p < 0.05$ ). All failures to detect targets occurred on trials where the distractor fell to the right of the target, and GK reported that only a distractor was present (i.e. extinction occurred; note that this might also include extinction of the whole group). Extinction was decreased when targets and distractors were part of the same group.

On two-item absent trials GK made 255/288 correct rejections (89% correct). However some errors did arise in the illusory conjunction false alarm condition, when the distractors belonged to the same group. In this condition GK scored 26/48 (54%) correct when distractors fell in the same group compared with 44/48 (92%) correct when they fell in different groups; false alarms were more likely in the same group condition ( $\chi^2(1) = 15.24$ ,  $P < 0.01$ ). These false alarms were not due to feature misidentifications. Summing across trials with two vertical distractors and trials with two horizontal distractors, there were 92/96 correct responses (96%) in the 'same group' feature error conditions, and 93/96 (97%) in the 'different group' feature error conditions. Taking just the same group conditions into account, there were more false alarms in the illusory conjunction condition than in the feature error conditions (with either two vertical or two horizontal distractors) ( $\chi^2(1) = 34.79$ ,  $P < 0.001$ ).

It could be argued that the effect of grouping on false alarms in the illusory conjunction condition here reflects extinction when distractors fell in different groups. We noted that extinction did occur on different group trials when the target was present. GK may fail to make false alarms when the distractors fell in different groups because one of the distractors was frequently extinguished. We test the relations between illusory conjunctions and extinction directly in Experiment 10 here. Even with the current data, however, we can estimate the extinction effects on absent trials from those found on present trials: 16% in the same group condition and 36% in the different group condition. With the same rates of extinction on absent trials we would expect there to be 40 trials where two distractors are detectable within the same group, and 31 trials where they are detectable but in different groups. There were still proportionately more false alarms in the illusory conjunction condition when distractors fell in the same group (22/40) than when they fell in different groups (4/31;  $\chi^2(1) = 6.98$ ,  $P < 0.01$ ).

In the different group conditions, there were 46, 45 and 46/48 correct rejections of target absent trials when distractors were respectively closely spaced, moderately spaced and widely spaced (summing across the illusory conjunction and feature error conditions). Taking just the illusory conjunction condition alone, there remained no effect of distance between the distractor elements (15, 14 and 15/16 correct rejections as the distance increased).

These results show that grouping affected both the rate of extinction and the likelihood that illusory conjunctions occurred, when we examined illusory conjunctions in the form domain. These illusory conjunctions occurred under forced-choice conditions and could not be accounted for by feature misidentifications. We conclude that these errors are produced by impaired per-

ceptual binding of parts but that, for form elements, this binding of parts is modulated by grouping between more global elements in the visual field.

### 3.10. General discussion

Across eight experiments we have shown that GK makes illusory conjunction errors even with relatively long stimulus durations (often of the order of 2 s, with unmasked items) when multiple stimuli are presented simultaneously. In every study with simultaneously presented items, illusory conjunction responses have been more frequent than feature misidentification errors and we have also shown that the effects are preserved even with forced-choice identification procedures (Experiments 6 and 8). When items are presented sequentially for the same durations, however, illusory conjunction errors are effectively eliminated (Experiment 7). Thus these errors seem to be perceptual in nature (occurring when memory influences are limited) and to emerge when there is simultaneous competition for the correct binding of features in stimuli. Illusory conjunctions have been found both between form and surface features (Experiments 1–6) and between form elements (Experiment 8). However, we have also demonstrated that these two types of illusory conjunction differ. Illusory conjunctions of form and surface features were unaffected by whether elements grouped (Experiments 3 and 4). We tested grouping by common enclosure, by contrast polarity, shape similarity, collinearity and connectedness, and in each case the proportion of illusory conjunction errors was the same whether elements originated from the same or from different groups (relative to the level expected from feature misidentifications). On the other hand, illusory conjunctions between form elements were more likely when the elements were part of the same group than when they were parts of different groups (Experiment 8). This is consistent with the proposal that the two forms of illusory conjunction arise at different stages of visual processing.

In addition to demonstrating a difference between the binding of form elements and the binding of colour and form, we also found that grouping moderated extinction. GK showed some recovery from extinction when elements grouped. This replicates prior data with both GK and other patients, but using identification rather than detection procedures (cf. Ward et al., 1994; Gilchrist et al., 1996; Mattingley et al., 1997). One other finding to note is that there were few effects on illusory conjunctions of the relative sizes of stimuli or of their relative distances; the only effect of size emerged under forced-choice conditions, with performance being worse when targets and distractors fell in the same spatial area and were similar in size (Experiment 6b). We suggest that this last result reflects competition between target and distractor features when (i)

GK was able to set an attentional window to the location of targets and (ii) distractors occupied a nearby position.

## 4. Effects of visual field and the relations between extinction and illusory conjunctions

So far we have shown a positive effect of grouping on visual extinction and little effect on illusory conjunctions of form and surface detail (contrast polarity, colour). This evidence dissociating the two phenomena relies on a null effect of grouping on illusory conjunctions. In Section 2 we report experiments that demonstrate a positive effect of one factor on form-colour illusory conjunctions: whether elements are presented within the same or in different hemifields. In addition, we contrast within-hemifield effects with effects of item position across the hemifields, which significantly influences extinction in GK. The evidence again dissociates extinction and illusory conjunctions, as well as helping to constrain our understanding of how form and surface details are bound in vision.

### 4.1. Experiment 9: illusory conjunctions within and across hemifields

Effects of hemifield on visual discrimination can be informative about the level in the visual system where a variable influences performance. Cells in initial visual areas of cortex are retinotopically coded, though the receptive fields increase at higher cortical levels (Zeki, 1993). In the inferior temporal lobe, for example, cells can have large receptive fields, often covering the central 30° or so of field (Gross, Rocha-Miranda & Bender, 1972). Due to their large fields such cells may be good candidates for the locus of illusory conjunctions, since the cells will be likely to fire to the attributes of multiple items in the visual field (see Treisman, 1998). On the other hand, if illusory conjunctions occur more frequently between stimuli in the same hemifield than between stimuli that are equally distant but in the other hemifield, this would suggest that cells at earlier visual levels are responsible (where hemifield is still represented). Effects of hemifield on illusory conjunctions have not been examined hitherto. Cohen and Rafal (1991) did report effects of hemifield on a patient with a left parietal lesion, but their main concern was with the contrast across the patient's ipsi- and contralesional fields. They did not evaluate whether illusory conjunctions were more likely to occur within than across hemifields. Here we assessed effects of hemifield in GK. Due to GK having bilateral lesions, there should be deficits within each hemifield (though performance may be worst on the left). Are illusory conjunctions more likely within each hemifield than they are across hemifields?

#### 4.1.1. Method

We used a two-alternative forced-choice procedure, in which GK had to decide whether a red circle target was present in a display. The other stimulus attributes assigned to distractors were blue, yellow, square and triangle. The stimuli were 0.5 in. across at their widest point and they could be centred at one of four locations on the corners of a virtual square, equidistant from fixation ( $x, y$  locations  $\pm 0.5$  in. from fixation). Two stimuli were always presented, either within the same hemifield (top and bottom positions, in either the left or right fields) or across different hemifields (left and right locations, in either the top or bottom field). The target, when present, was paired randomly with one of the four possible distractors, in each of the possible locations (half in the same hemifield and half in opposite hemifields). Stimuli were presented for either 1 s (eight blocks of trials) or for 200 ms (to minimise eye movements; seven blocks of trials). The first two blocks of trial at the long duration contained 144 trials each, with 32 target present displays and 112 target absent. On target absent trials there were four conditions: (a) illusory conjunction false alarms (where each distractor had one target property; 32 trials); (b) colour feature error (where one distractor had the target shape but neither had the target colour; 32 trials); (c) shape feature error (one distractor had the target colour but neither had the target shape; 32 trials); and (d) neither feature trials (neither distractor had a target feature; 16 trials). For the remaining 6 blocks of trials there were 192 trials per block, 96 present and absent (omitting the trials on which the distractors did not share any target features). For the short duration, the blocks contained 196 trials. Stimuli were presented on a Macintosh quadra using the VScope package. When GK missed a target he was asked to report the attributes he perceived (as in Experiment 6).

#### 4.1.2. Results and discussion

The total numbers of correct responses, and the numbers of each type of error, are given in Table 10.

The data were analysed by summing the total number of target feature misidentification errors (shape + colour feature) and comparing them with the number of illusory conjunctions in a trial block in an ANOVA, with trial block treated as subjects. The within-subjects factors were: same or different hemifield, present or absent response, and type of error (illusory conjunction vs. feature). There was one between-subjects factor: display duration. There were no reliable main effects but there were interactions between type of error and display duration ( $F(1,13) = 7.94, P < 0.02$ ), and between present/absent response, type of error and duration ( $F(1,13) = 4.91, P < 0.05$ ). These interactions arose because, at the longer duration, there were proportionately more illusory conjunction to feature errors on

target present trials; in contrast at the short duration there were more illusory conjunction than feature errors on absent trials (compare Table 10a and b). At the longer duration the effect of error type was reliable on present trials ( $F(1,7) = 16, P < 0.01$ ). At the short duration it was marginally significant on absent trials ( $F(1,6) = 4.03, P = 0.09$ ).

When the exposure duration was reduced, GK's overall level of performance decreased from around 85% correct to around 65% (cf. Table 10a and b). Nevertheless at both durations GK tended to make more illusory conjunction than feature misidentifications, and this was unaffected by whether two stimuli were presented within the same or across different hemifields. The main effects of reducing the exposure duration were to increase the number of target misses (misses occurred on about 40% of the target present trials at the short duration, but only about 6% of the present trials with a longer duration) and to increase shape feature errors. Feature errors may tend to arise when there are constraints on coding as well as binding feature elements. Also the tendency to find illusory conjunctions was more prevalent on target present trials at the long duration and on target absent trials at the short duration. It is not clear why this last difference occurred. However, there was no indication that illusory conjunctions were less frequent when the stimuli appeared in different fields relative to when they fell in the same field. In the different field condition, the stimuli were separated along the horizontal dimension, and there can be relatively strong extinction of left-side items under these conditions (Gilchrist et al., 1996; see Experiments 2–4 here). Despite this, illusory conjunctions involving one attribute from the left-most item were still apparent under the present forced-choice test conditions.

In Experiment 10 we explored the effects of hemifield on grouping effects in extinction, to test again whether contrasting results emerged relative to when illusory conjunctions of shape and surface detail were measured (in Experiment 9).

#### 4.2. Experiment 10: grouping on extinction, within and across hemifields

In Experiment 10 we used similar displays to those employed in Experiment 9, in order to examine whether hemifield influenced the effects of grouping on extinction. A forced-choice task was again used: GK had to detect the presence of a black square. When present this appeared alone or with either a white square, a black circle or a white circle. Experiment 4 here (also Gilchrist et al., 1996) demonstrated that there is grouping (i) between squares even when they have opposite contrast polarities, and (ii) between two shapes having the same polarity and/or luminance. In contrast, group-

Table 11

Number (and percentage) of trials for which there was correct target detection in Experiment 10, as a function of grouping condition (present trials) and distractor type (absent trials)

|                                       | Shape group □■           | Colour group ■●  | No group ■○       |
|---------------------------------------|--------------------------|------------------|-------------------|
| <i>(a) Present trials<sup>a</sup></i> |                          |                  |                   |
| Same hemifield                        | 28 (87.5)                | 26 (81.3)        | 12 (37.5)         |
| Different hemifield                   | 21 (65.6)                | 19 (59.4)        | 11 (34.4)         |
|                                       | Illusory conjunctions □● | Shape feature ○● | Colour feature □○ |
| <i>(b) Absent trials<sup>b</sup></i>  |                          |                  |                   |
| Same hemifield                        | 29 (90.6)                | 30 (93.8)        | 31 (96.9)         |
| Different hemifield                   | 30 (93.8)                | 31 (96.9)        | 31 (96.9)         |

<sup>a</sup>  $N = 32$  per cell

<sup>b</sup>  $N = 32$

ing should be minimal between stimuli differing in both shape and luminance (e.g. a black square and a white circle). For a black square target there should be extinction relative to single item trials when a white circle distractor is presented (especially when the distractor falls in a ‘preferred’ area of field), and extinction should be reduced by grouping when other distractors are used (sharing shape and collinearity, with two squares; sharing contrast polarity/luminance with a black square and a black circle). We test whether these grouping effects are stronger when the shapes appear within the same hemifield relative to when they appear in different hemifields. In addition we assessed whether illusory conjunctions arise and how they vary when stimuli appear in the same or in different hemifields. For example, on target absent trials GK could be presented with a black circle and a white square. Are false positive responses then more likely, relative to when the distractor shapes only have one attribute in common with the target (e.g. with a black circle and a white circle, or with a white square and a white circle)? Are false positives due to illusory conjunctions more likely when distractors appear within the same hemifield than when they are presented in different hemifields?

#### 4.2.1. Method

The stimuli were 0.5 in. at their widest points and appeared centred at locations  $\pm 0.5$  in. from fixation on the  $x$  and  $y$  dimensions (at the corners of a virtual square). The target was a black square and distractors were white squares, black circles and white circles. On single item trials, either the target or a distractor appeared at one of the four potential locations. There were 12 target present and 12 absent trials per block (on absent trials each distractor appeared four times, once at each display location). For two item displays there were 96 present and 96 absent trials per block. On present trials the target was paired equally often with each distractor type and it appeared in each display location equally often. The distractor appeared in the

same hemifield as the target on half the trials (both left or both right of fixation), and it appeared in the opposite hemifield on the remaining trials (both left or both right of fixation). This created three grouping conditions, each with 32 trials per block: (i) same shape (white square distractor); (ii) same colour (black circle distractor); and (iii) different shape and colour (no group condition; white circle distractor). On absent trials there were also three conditions: (i) illusory conjunctions (black circle and white square distractors); (ii) shape feature error (black and white circle distractors — here a false positive response would indicate poor processing of the distractor shapes); and (iii) colour feature error (white square and circle distractors — here a false positive response would indicate poor processing of the distractor colours). The task was to decide whether a black square was present. If there was an error on a present trial, GK was asked to report the colours and shapes he had seen. He took part in two blocks, each with 216 trials. Displays were presented for 1 s.

#### 4.2.2. Results and discussion

GK made few errors on single item trials, scoring 23/24 on present and 22/24 on absent trials. The errors were all to items presented in his left field (one to an item in the top left and two to items in the bottom left position). The number of correct responses on target present trials are given in Table 11. On present trials, performance was better in the grouping conditions relative to the condition in which the target and distractor differed in both shape and colour ( $\chi^2(1) = 19.84$  and  $13.84$ , both  $P < 0.01$ , for the comparison of group by shape and group by colour with the no group baseline, summing across hemifields). However, target detection in the grouping conditions was better when the target and distractor fell in the same hemifield than when they appeared in different hemifields (summing across the two grouping conditions,  $\chi^2(1) = 6.77$ ,  $P < 0.05$ ). In the grouping conditions, performance was at the same

level as for single item trials when the stimuli fell within the same hemifield ( $\chi^2(1) = 1.1.8, P > 0.05$ ). Performance was worse than the single item baseline when targets and distractors fell in different hemifields ( $\chi^2(1) = 8.0, P < 0.01$ ). In the no group condition, performance was worse than in the single item baseline, even when items fell in the same hemifield ( $\chi^2(1) = 17.5, P < 0.01$ ).

Of the errors made on two item, present trials in the grouping condition, 26/34 (76%) were due to misses of the target, with GK reporting just the distractor shape and colour on those trials. Misses were more frequent in the different than in the same hemifield condition (17 to 9). The remaining errors were primarily shape misidentifications in the group by shape condition (6: GK reported a black circle instead of the black square target), along with two complete misses in the group by colour condition (GK reported no items on these trials). In the no group condition, 27/41 (66%) of the errors were due to target misses. The other 14 errors comprised nine with complete feature exchanges (black square and white circle  $\rightarrow$  black circle and white square), and five where GK reported one item with one feature of the target (e.g. black circle). These last errors could be illusory conjunctions or feature misidentifications. However, using the single item feature errors (on two item trials) as an estimate of these types of mistake, we would expect complete feature exchanges on just 0.4 trials. Complete feature exchanges were more frequent than this, suggesting that illusory conjunctions did occur. There were 15 target misses in the different hemifield condition and 12 when the items fell in the same hemifield. There were eight illusory conjunction/feature misidentifications in the same hemifield condition (five complete feature exchanges) and six in the different hemifield condition (four complete feature exchanges). There were no strong effects of hemifield on error proportions.

GK made few errors on absent trials when two items were present, perhaps due to a bias to respond absent. The effects of distractor type (illusory conjunction versus shape feature versus colour feature) and of hemifield did not approach significance.

These data indicate that the effects of grouping on target detection are influenced by whether or not stimuli appear in the same hemifield. There were stronger effects of grouping when targets and distractors were in the same hemifield than when they were in different hemifields. This was not due to some overall benefit when items appeared in the same hemifield. In the no group condition there was little effect of hemifield. Thus, at least for a patient such as GK with bilateral lesions, extinction per se does not seem stronger when items were presented in different rather than the same

hemifield<sup>2</sup>. Rather there is a selective effect of grouping, which is increased when items fall in the same hemifield. Thus the locus of the grouping effect seems to be sensitive to whether stimuli cross GK's midline. This suggests that the grouping effects are influenced by coding taking place within visual areas preceding inferotemporal cortex, where the receptive fields of cells are bilaterally represented (Gross et al., 1972).

Alternatively, it might be argued that the present effects were not due to hemifield but rather to the alignment of the shapes. In the same hemifield condition shapes were vertically aligned; in the different hemifield condition shapes were horizontally aligned. Although this alignment did not appear to affect extinction in the no group condition for GK (given that extinction was equally severe in the two hemifield conditions; see above), it might have affected grouping. We have tested for this in a control study in which GK received stimuli in either horizontal or vertical alignments, always in the same hemifield. The stimuli were drawn from just the 'group by shape' condition, and the task was the same as in Experiment 10 (is there a black square?). Shapes appeared at one of four locations in either the right or left fields,  $\pm 0.5$  or  $\pm 1.25$  in. from fixation. When horizontally aligned, stimuli appeared in the upper locations on half the trials and the lower locations on the other trials. When vertically aligned, stimuli appeared in the near locations on half the trials and the far locations on the remaining trials. Absent trials used the same shapes as for the absent responses in Experiment 10. There were 112 trial altogether, 64 target present (32 with horizontal and 32 with vertical alignments) and 48 absent (16 for each combination of distractor shapes). Stimuli were again presented for 1 s. GK performed well, scoring 51/64 on present trials and 47/48 on absent (one false positive in the illusory conjunction condition, with vertically aligned shapes). There was no effect of alignment on present trials (24/32 with horizontal and 27/32 with vertically aligned shapes;  $\chi^2 < 1.0$ ). We conclude that there were effects of hemifield, but not alignment, on grouping.

#### 4.3. Discussion

The data in Section 2 have shown that illusory conjunctions of shape and surface detail are unaffected

<sup>2</sup> It might be argued that extinction was stronger in the different hemifield condition, since it misses were then more likely (32 vs. 21, summing over the grouping conditions). On the other hand, other forms of error (illusory conjunctions, feature misidentifications) were also more likely then (13 vs. 9). For the grouping conditions, performance was generally worse in the different hemifield condition, due to grouping then being weaker, but the proportions of errors did not change ( $\chi^2 < 1.0$ , for a comparison of misses to other errors, for the same and different hemifield conditions).

by whether objects fall within the same hemifield: illusory conjunctions were as likely when items fell in the same hemifield as when they appeared in different hemifields (Experiments 9 and 10). In contrast, effects of grouping on extinction were stronger when shapes fell within the same hemifield than when they fell in different hemifields. This suggests that grouping effects are influenced by stages of processing in which cells remain sensitive to the hemifield into which stimuli fall,

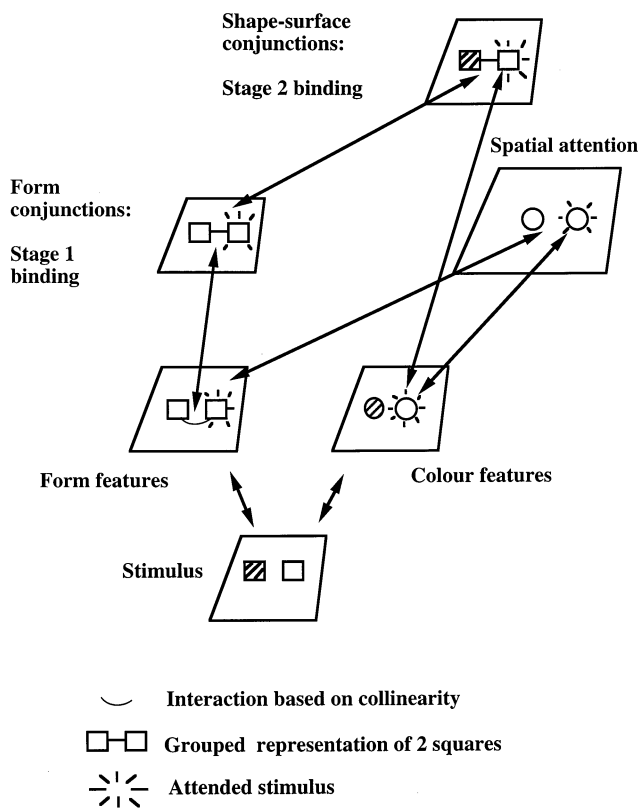


Fig. 7. A two-stage framework for binding shape and surface details. In the figure, a stimulus is presented with two squares in close proximity but differing in colour. The shapes and their colours are coded in separate processing streams (once response to shape but not colour; one to colour but not shape). In this example attention is paid to the right-most stimulus, activating the early coding of its shape and colour in the separate maps. Other items in the field would be unattended and fail to activate higher-level representations. However, since the stimuli here are both spatially proximal and collinear, there is cross-activation of their representations in the form domain (left-side of figure). This leads to activation of a representation of the form conjunction, in which the two shapes are coded together even though only one of them is attended; this is the first stage of feature binding. Once a representation for both shapes is formed, there will then be activation of the spatial attentional system to cover both items, so that the two shapes and colour become attended. The shapes and colours present activate higher-level units (e.g. conjunctions of shape and surface features), enabling their properties to be bound: the second stage of binding. In a patient such as GK we assume that there is an impairment in spatial attention. This disrupts the binding of shape and surface information, since unattended elements could compete for binding at the second stage. Binding at the first stage, though, can proceed even without the influence of attention, so that grouping effects are found on object detection.

whilst illusory conjunctions occur at a later processing stage where cells respond to bilateral input. As in Section 1, there is a dissociation between illusory conjunctions of shape and surface detail and grouping effects based on form information.

## 5. General discussion

We have found that GK, a patient with Balint's syndrome following bilateral parietal lesions, shows extinction (especially for left-side items) along with substantial numbers of illusory conjunctions of both form, and form and surface detail, even with displays presented for long durations (1–2 s). The main results were that: (a) extinction and illusory conjunctions of form were both affected by grouping between form elements; (b) illusory conjunctions of shape and surface detail were indifferent to form-based grouping; (c) illusory conjunctions of shape and surface detail were unaffected by whether items fall in the same hemifield, whilst grouping was stronger within than across hemifields.

### 5.1. Grouping, extinction and illusory conjunctions: a two-stage account of binding

The present data suggest a two-stage account of binding, in which elements are first grouped into objects, and surface properties then assigned to those objects. Early, apparently pre-attentive, grouping of form information into objects is demonstrated by the effects of grouping on recovery from extinction (see below). The lack of an effect of grouping on illusory conjunctions of shape and surface detail, however, suggests that these properties of objects are only integrated at a second stage. It is this second stage that is particularly impaired for GK. We elaborate this account in Fig. 7.

The two maps on the bottom left side of Fig. 7 illustrate the first stage of 'binding by form'. We propose that binding by form operates within the ventral visual system, and it involves grouping form elements based on bottom-up stimulus properties (e.g. collinearity, connectedness and common enclosure) along with re-entrant top-down activation from stored object descriptions. These stored object descriptions would be represented at the level of form conjunctions in the framework.

Evidence for this first stage of binding comes from the effect of grouping on visual extinction in neuropsychological patients. The current data show effects of various bottom-up grouping cues: common enclosure, contrast polarity, shape similarity, collinearity and connectedness (see also Ward et al., 1994; Gilchrist et al., 1996; Mattingley et al., 1997; Humphreys, 1998). Top-

down effects on grouping based on stored knowledge are indicated by reduced extinction with words over non-words, even though there are few bottom-up cues favouring the grouping of letters in words over those in nonwords (Kumada & Humphreys, submitted). Since grouping between items can lead to items being detected that would otherwise be extinguished, we conclude that the grouping relationships are computed pre-attentively, prior to the patient even being aware of the presence of the stimuli.

We have also found that grouping affects illusory conjunctions between form elements. Local lines were more likely to be conjoined when they formed parts of a more global object than if they were parts of different objects. This same pattern of performance occurs with normal subjects too (Prinzmetal, 1981), so there is nothing qualitatively unusual about GK's performance in this respect (though the effects are unusually large, particularly when we take stimulus duration into account). The fact that grouping influences perceptual binding, however, is difficult to account for in terms of some theories of binding. For example, according to FIT (Treisman, 1998), binding is determined by attention to the common location of stimuli, prior to grouping by form taking place. Contrary to this, the data suggest that some form of primitive binding constrains whether parts of forms are subsequently conjoined within an overall (grouped) shape (e.g. the line elements within the squares or circles, in Experiment 8).

If form elements can be bound pre-attentively, why should there be illusory conjoining of their parts? One possibility is that any initial binding of shape is coarse, perhaps because the receptive fields of cells are not optimally tuned to the location of the stimuli (cf. Moran & Desimone, 1985; Desimone & Duncan, 1995; Connor, Gallant, Preddie & Van Essen, 1996; Desimone, 1998). Consistent with this argument for initial coarse coding, some researchers have shown that features are more likely to form illusory conjunctions if they are spatially proximal (Cohen & Ivry, 1989), though this is by no means a universal finding (see Treisman, 1998). Stable binding takes some time to occur and for normal observers it is disrupted by limiting the stimulus exposure time and by adding a secondary task load. It also appears to be disrupted by damage to the parietal lobe in a patient such as GK (see also Friedman-Hill et al., 1995). The parietal lobe may be important in re-tuning receptive fields of cells within the ventral visual system, perhaps by re-entrant activation through early visual areas (cf. Moran & Desimone, 1985); this may be equivalent to 'allocating visual attention' to the location of a stimulus, as proposed by FIT. In Fig. 7, this process is illustrated by the arrows that signify the feedback of activation from a visual attention system (in the parietal lobe) to early visual representations. This location-based feedback helps to prevent those cells in the ventral visual system

with large receptive fields from being activated by features that are spatially separated or from different objects. In addition to this parietal feedback, we also suggest that early activation is affected by top-down excitation of features from the object-recognition system, following the coarse binding process (cf. Farah, 1990; Humphreys & Riddoch, 1993). As a consequence, form elements within the same object should be co-activated above those in different objects. This feedback will apply only to form elements; it will not bind form and surface features together unless objects have known surface properties. It follows that form elements within the same object are more likely to be conjoined (due to conjoint activation of higher-level cells) than form elements in different objects. Damage to the parietal lobe will make report susceptible to illusory conjunctions of form, however, since cells within the ventral visual system will be tuned too broadly. The parietal lobes (particularly around the temporo-parietal junctions, lesioned in GK) are also implicated in switches of attention between stimuli, and in switching attention from one spatial scale to another (Posner, Walker, Friedrich & Rafal, 1984; Robertson, Lamb & Knight, 1988). Switches from a global to a more local scale of coding may be important for binding parts of forms, in order to prevent errors when there are multiple parts present (e.g. with one part being bound into the wrong position in the global shape). Due to his parietal lesions, GK may be impaired at establishing stable bindings of form elements, following the initial coding of more global shape descriptions. It is interesting in this respect to note that GK is an attentional dyslexic (cf. Shallice & Warrington, 1977; see also Baylis, Driver, Baylis & Rafal, 1994; for evidence from another patient with Balint's syndrome). Thus he can often read whole words but not their letters. Indeed his identification of letters within strings is very prone to positional migrations, and his word identification instead seems more reliant on non-decomposed pattern information (Hall et al., submitted). This is exactly what we might expect if GK can bind forms at a coarse global scale, but has difficulty in subsequently binding parts (both features within letters and letters to their locations).

The second stage of binding is illustrated in the full framework, including the right side maps in Fig. 7. In this framework, higher-level cells in the ventral visual system can respond to conjunctions of form and surface property, binding the two forms of information together (cf. Tanaka, 1993). As suggested by FIT, activation from the parietal system, to locations commonly occupied by the form and surface properties, is needed to prevent illusory conjunctions from arising when there are multiple items present. Parietal activation biases selection so that only features from a shared location are excited, allowing them to be bound together by common activation of the same high-level cell(s). Within our framework, top-down



activation from the object recognition system to early visual features can also ‘push’ the parietal system so that the ‘grouped locations’ (Vecera & Farah, 1994) become attended.

Our argument for a second stage of binding, for form and surface detail, comes from our failure to find effects of grouping or hemifield on illusory conjunctions in GK. GK showed abnormal numbers of conjunctions of shape and surface detail, even with prolonged viewing times, suggesting an impairment in binding these properties. However the proportions of illusory conjunctions to feature misidentifications was the same irrespective of whether form elements combined into a single object or into two objects. This indicates that the surface details of objects were not treated in the same way as object parts, whose coding was modulated by grouping. This contradicts theories that hold that there is a single binding process, operating in the same way for object parts and for surface properties (cf. Treisman, 1998). We propose that the initial binding of form into global shape, a process mediated by ventral cortex, is relatively intact in GK. In contrast, his parietal lesions disrupt both the binding of local parts within shapes (see above) and the binding of shape to surface detail. Without parietal involvement, surface information may be linked to form in a relatively unconstrained way, even when initial form binding has taken place. For example, high level cells may be activated by shapes and colours present within broad regions of field, so that illusory conjunctions of form and colour result. Indeed, Experiments 9 and 10 indicate that illusory conjunctions of shape and surface detail were unaffected by whether stimuli fell within the same hemifield, whereas hemifield was important for grouping. This last result is consistent with shape-based grouping operating within early stages of vision, sensitive to field position. In contrast, conjunctions of colour and form are formed at a later level where cells have bilateral representation. Cells in area IT are a good candidate for this (Gross et al., 1972).

One difference between the results for GK here and prior data with normal observers is that, for normal observers, form and colour binding seem to be affected by object coding—a result we confirmed with age-matched controls in Experiment 4 here (see also Prinzmetal et al., 1986). It seems that even when experimental conditions limit normal attention to the stimulus (through reduced exposures, secondary tasks etc.), the coding that takes place is still modulated by object knowledge (though the resultant binding is form and colour may not be stable without attention). On our account form-colour binding should normally be modulated by object coding, because top-down activation from object representations biases attention towards grouped locations. In GK’s case, however, bilateral parietal damage minimises the role of

spatial attention on performance. Colour information consequently becomes ‘free floating’ and unconstrained in its binding by object properties.

The two-stage account of binding that we propose, in which form binding into primitive object representations precedes the binding of form and surface detail, can be related to the account of binding suggested by Grossberg and colleagues (Grossberg & Mingolla, 1985; Grossberg & Pessoa, 1998). The form binding effects found with GK may reflect the operation of the BCS, which acts to group form elements into putative objects. The binding of surface details to shape would normally operate through the FCS. We posit that activation in the FCS must be co-ordinated with that in the BCS, so that form and surface details are integrated accurately; this co-ordination operates through co-activation of early location-coded representations occupied both by the object and the surface properties. GK has sustained damage to this co-ordination process, leading to relatively unconstrained integration of form and colour. There does not seem to have been damage to the FCS itself, though, since GK can discriminate basic colour features; he is simply poor at assigning them to the appropriate form.

It is also possible to conceptualise the grouping effects on extinction in terms of binding by temporal synchrony — a process which may operate rapidly in a spatially parallel manner (e.g. Elliott & Müller, 1998). However, there would still need to be some further account of the dissociation between the grouping effects on extinction, and the failure to find similar results on illusory conjunctions of shape and surface property. For example, it might be that the binding of shape and surface detail depends on longer-range connections than the binding of local form elements, and these longer-range connections may be selectively disrupted. It may also be that disruption of synchronisation across dimensions could ‘undo’ synchronisation within a dimension, eliminating effects of grouping on cross-dimension integration. These speculations require further exploration.

## 5.2. *Illusory conjunctions and extinction*

Our results have indicated a dissociation between extinction and illusory conjunctions, with only extinction affected by grouping. We have accounted for this in terms of a two-stage theory of binding. An alternative to this is that the contrast between extinction and illusory conjunctions reflects a difference between explicit and implicit stimulus processing. Effects of grouping occur implicitly — in the sense that GK does not have to be aware of grouping taking place, he simply responds to the products of this process. In contrast, illusory conjunctions of shape and surface detail arise in tasks where GK has to report both shape and surface information. It may be that implicit measures are more sensitive to grouping than explicit measures of performance.

There are reasons to doubt this argument, though. For example, we did find effects of grouping on illusory conjunctions in the form domain (Experiment 8), using a similar task to that employed with conjunctions of shape and surface detail (e.g. Experiment 6). Also it is by no means clear whether forced-choice discrimination tasks, used here to study illusory conjunctions, ‘tap’ implicit or explicit processes (see Young & de Haan, 1990); in fact performance on forced-choice discrimination tasks has sometimes been taken as evidence for implicit processing, as in studies of blindsight (Weiskrantz, 1986). We conclude that the difference cannot be understood simply in terms of the sensitivity of implicit and explicit tasks to grouping.

Nevertheless it is of interest to note that GK is very impaired at explicit location judgements to visual forms even when the elements grouped together. Humphreys et al. (1994), for example, reported that GK was at chance at identifying whether stimuli fell either above or below fixation; yet, at the same time, he was better at discriminating targets that grouped with distractors than targets that did not group. These data fit with the proposal that the parietal lobe provides an explicit spatial representation of an object — perhaps one that can be used for action. In contrast, though grouping within the ventral visual system is sensitive to the relative spatial relations between visual elements, which are coded implicitly. For instance, within the ventral system variations in the spatial relations between ‘parts’ affect the activation of stored object representations, but judgements of the same spatial relations will then require the selection of each part as a separate object and use of the position code represented within the parietal system. GK is impaired at this process. Indeed, GK’s symptoms of attentional dyslexia match exactly this account: there is relatively good identification of words (using implicitly position coding of letters) along with severely impaired identification of letters (requiring explicit coding of letter locations).

### 5.3. *Other factors affecting illusory conjunctions*

The likelihood that GK made illusory conjunctions was relatively little affected by factors such as the distances between objects or their relative sizes. The only effect of size was found under forced-choice identification conditions (Experiment 6b), when stimuli were centred on fixation. Effects under these circumstances may be due to GK trying to fix an attentional window on a target shape and/or colour, and this window is then maintained for selection of both the stimuli present. Under free report conditions, GK may be less able to do this since there are no consistent target attributes available to guide attention efficiently. With normal observers, at least some data suggest that distance information is important (Cohen & Ivry,

1989), suggesting that perceptual information is coarsely represented under conditions of brief exposure and high perceptual load. The distance effects with normal observers may alternatively be attributed to attention ‘zooming in’ to accommodate near neighbours without having sufficient time to resolve the two. Illusory conjunctions of the attended attributes then occur (Treisman, 1998). These accounts are not mutually exclusive though. The effect of focusing spatial attention on a target, by location-based modulation of receptive fields, may be to improve location coding and location coding may coarsen under high load conditions (see Prinzmetal, Amiri, Allen & Edwards, 1998). Our proposal for a two-stage binding process raises the question of whether lowering processing resolution in this way has the same impact on the binding of shape and on the binding of shape to surface detail. With GK, the answer appears to be ‘no’; lowered resolution of attention affects the binding of shape and surface detail but not the binding of elements into primitive visual objects.

### 5.4. *Binding and serial search*

According to FIT, serial search is typically found for conjunction targets because of the need to bind their features together. It is entirely consistent with this account, then, that a patient with poor feature binding should also show impaired serial search for conjunction targets (see Friedman-Hill et al., 1995). GK has impaired serial search for both form-colour conjunctions and also for putative form conjunctions (T vs. L search; see Section 2.1). However we have also argued that GK has a relatively preserved ability to group form elements together along with impaired binding of form and colour. Why then should GK be impaired at search for form conjunctions as well as form-colour conjunctions? We attribute GK’s poor search for form conjunctions (as well as form-colour conjunctions) to his impaired ability to code stimulus location and to use location information to direct a systematic serial search across a display. When targets and distractors share elements, search can be difficult even for feature targets, requiring some serial selection of the items present. Serial selection will in turn depend on a number of processing operations, including inhibition of those items initially selected and competition between remaining items depending on spatial and other properties. Both the ability to inhibit selected items, as well as spatial selection itself, can be disrupted by parietal damage (cf. Posner et al., 1984). As a consequence, serial search can be affected even if binding is relatively preserved. We suggest that impaired serial search should not be taken as necessarily indicative of impaired binding. Indeed, as we have noted, when asked to perform tasks such as identifying letters within a

string GK typically makes correct whole letter responses but in the wrong spatial order; however illusory conjunctions between letters are difficult to observe (Hall et al., submitted). This is consistent with the features within letters being bound together, but with GK being impaired in the ability to select individual letter representations based on their explicit locations within the strings.

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