

Simultanagnosia: When a Rose Is Not Red

H. Branch Coslett^{1,2} and Grace Lie

Abstract

■ Information regarding object identity (“what”) and spatial location (“where/how to”) is largely segregated in visual processing. Under most circumstances, however, object identity and location are linked. We report data from a simultanagnosic patient (K.E.) with bilateral posterior parietal infarcts who was unable to “see” more than one object in an array despite relatively preserved object processing and normal preattentive processing. K.E. also demonstrated a finding that has not, to our knowledge,

been reported: He was unable to report more than one attribute of a single object. For example, he was unable to name the color of the ink in which words were written despite naming the word correctly. Several experiments demonstrated, however, that perceptual attributes that he was unable to report influenced his performance. We suggest that binding of object identity and location is a limited-capacity operation that is essential for conscious awareness for which the posterior parietal lobe is crucial. ■

INTRODUCTION

Simultanagnosia, initially described by Balint (1909) as a component of the syndrome that bears his name, is a disorder characterized by the inability to see more than one object at a time. Patients with this disorder typically exhibit a striking deficit in apprehending the visual world. When confronted with complex arrays such as a dinner table laden with food and utensils, simultanagnosics will often report seeing only a single item such as a fork.

Investigations of patients with simultanagnosia can provide important insights regarding the nature of normal visual perception and its neural basis (Robertson & Treisman, 2006; Coslett & Chatterjee, 2003; Humphreys & Riddoch, 2003). Here we address two major issues: the manner in which spatial and object representations are integrated and the relationship between perception and awareness. The former issue, a major element of the “binding problem,” has a venerable history in cognitive neuroscience (Treisman, 1998). Treisman’s Feature Integration Theory (FIT) proposes that attention serves to link visual features and location (see also Wolfe, 1994). On this account, visual features such as angle, color, and curvature are processed in different feature maps. Feature maps are assumed to be linked to a representation of space, the “Master Map of Locations,” subserved by the parietal lobes (Robertson, 2003; Treisman, 1998; Treisman & Gelade, 1980). Directing attention to a location at the Master Map of Locations serves to highlight the corresponding location in the visual feature maps with the consequence that the distinct features at that

location are linked to the same location. The attention-requiring process of binding visual feature information can be disrupted in normal subjects by reducing stimulus presentation time or, in patients with brain dysfunction, by lesioning the parietal lobes (McCrea, Buxbaum, & Coslett, 2006; Robertson & Treisman, 2006; Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997). One consequence of this disruption is the production of “illusory conjunction” errors in which visual features are miscombined to produce a percept that is, in fact, not present in the array. For example, McCrea et al. (2006) reported that their patient, E.D., reported seeing a red T when shown an array containing red “S”s and green “T”s (see also Humphreys, Cinel, Wolfe, Olsen, & Klempen, 2000; Friedman-Hill, Maldonado, & Gray, 1995). Although FIT was developed to account for binding of visual information in early vision, illusory conjunctions have also been demonstrated with more complex stimuli such as letters and even words. In the latter instance, letters may be mislocated so that subjects report words not present in the array (e.g., mean read as “amen”; McCrea et al., 2006; see also Robertson et al., 1997).

If the posterior parietal lobes represent the neural substrate for the Master Map of Locations and this representation is crucial for linking low-level visual feature information, how can simultanagnosic subjects recognize complex objects that are composed of multiple distinct features in a precise spatial arrangement? One explanation, originally proposed by Shalev and Humphreys (2002), Humphreys et al. (2000), and Humphreys (1998), appeals to the well-established distinction between the dorsal and ventral visual pathways (Ungerleider & Mishkin, 1982). On this proposal, the former, often designated as the “where” or “how to” (Milner & Goodale, 1995)

¹University of Pennsylvania School of Medicine, ²Moss Rehab Research Institute, Philadelphia, PA

pathway, provides an egocentric spatial representation that codes location in a manner appropriate for action, whereas the latter, often designated as the “what” pathway, computes object identity. Although recognizing that spatial information is crucial for both systems, Humphreys and colleagues suggested that the pathways differ with respect to the manner in which spatial information is employed; more specifically, they suggest that the dorsal system computes the spatial relationship between objects and the individual, whereas the ventral system computes the spatial relationship between elements that constitute the object.

Although the distinction between processes computing spatial relationships within and between objects offers an account of the observation that patients may produce illusory conjunctions at multiple levels of analysis—that is, within letters, between letters, within words, and even between words (Saffran & Coslett, 1996), the account does not provide a ready explanation for the paradigmatic deficit produced by simultanagnosic subjects: the inability to report more than one object in an array. The finding that simultanagnosic subjects often recognize only one item in an array raises the possibility that, at least for some patients with this disorder, the impairment reflects a deficit in the binding of object representations (or structural descriptions) to spatial information; we previously reported a patient with simultanagnosia for whom this account was offered (subject B.P.; Coslett & Saffran, 1991).

Here we report a simultanagnosic patient for whom there was no clear evidence of a deficit in feature integration. Like B.P. (Coslett & Saffran, 1991), his performance was influenced by the semantic relationship between the items in an array; he reported both items in two-item arrays more reliably if they were members of the same semantic category. Consistent with the hypothesis that binding of information computed in the ventral and dorsal pathways is a capacity-limited procedure, he exhibited a finding that has not, to our knowledge, been reported previously: He was not only unable to reliably report two objects, he was also unable to report more than one attribute of the *same* object. Finally, we demonstrate that the information about the objects that he was unable to report (the color of the word or line drawing) significantly influenced performance. We suggest that binding of object and identity is a limited-capacity operation that is essential for conscious awareness.

Patient Description

The patient (K.E.) was a 58-year-old factory worker with a high school education who noted the sudden onset of an inability to “see” and difficulty in performing routine tasks. K.E. had suffered an infarction of the left hemisphere causing minor language problems and clumsiness of the right hand 3 years prior to the investigations reported here. He suffered a second stroke 1 year prior

to this testing. His symptoms had persisted without significant change since the second stroke. When first seen approximately 1 year after the onset of his simultanagnosia, he was unable to direct his hands to a target; on several occasions, he started fires when attempting to snuff out cigarettes in an ashtray. He also stated that he was frequently unable to find objects in an array; he was typically unable to locate eating utensils and condiments when eating. The data reported here were collected over an interval of approximately 18 months, during which there was little change in his behavior.

Neurologic examination revealed him to be fully oriented. He manifested pyramidal clumsiness with both hands but no significant weakness. K.E. exhibited prominent misreaching to visualized targets (optic ataxia) with both hands. Gait was slow with short steps. There was no tactile or auditory extinction.

Assessment of visual processing revealed a visual acuity of 20/30 OU. When instructed to look at the examiner’s face without focusing attention, visual fields were full to confrontation; when asked to focus attention on the examiner’s nose, visual fields were restricted to approximately 30° concentrically with no evidence of a scotoma or asymmetry. He exhibited inconsistent extinction to double simultaneous stimulation in the left visual field. Ocular movements to command (e.g., look to the door), as well as smooth and saccadic pursuit, were normal in all directions.

Magnetic resonance imaging performed approximately 1 year after the onset of simultanagnosia revealed small areas of infarction involving the left middle temporal gyrus, the left middle frontal gyrus, and a larger left posterior parietal infarction. He had also suffered a right posterior parietal hemorrhagic infarction. Nonspecific increased signal in the subcortical white matter of both hemispheres was also noted on T2-weighted images (Figures 1 and 2).

Neuropsychological Examination

The neuropsychological assessment was limited by K.E.’s optic ataxia as well as his inability to consciously process more than one object at a time; the former prevented him from responding reliably on tasks requiring a pointing response. Spoken language was relatively preserved. He was fluent with an appropriate range of syntactic structure in spontaneous speech. Repetition of words and sentences was normal. He exhibited mild word finding problems in conversation and was slightly impaired in naming single objects. He named 48/60 words on the Boston Naming Test. There were three semantic errors, four circumlocutions, and five instances in which he named a part of the object. He description of the Cookie Theft picture was slow and labored; after approximately 10 min of scrutiny, he reported six people in the picture, apparently counting the girl thrice and the boy twice. He never reported most of the objects in the array and did not achieve a coherent understanding of the scene.

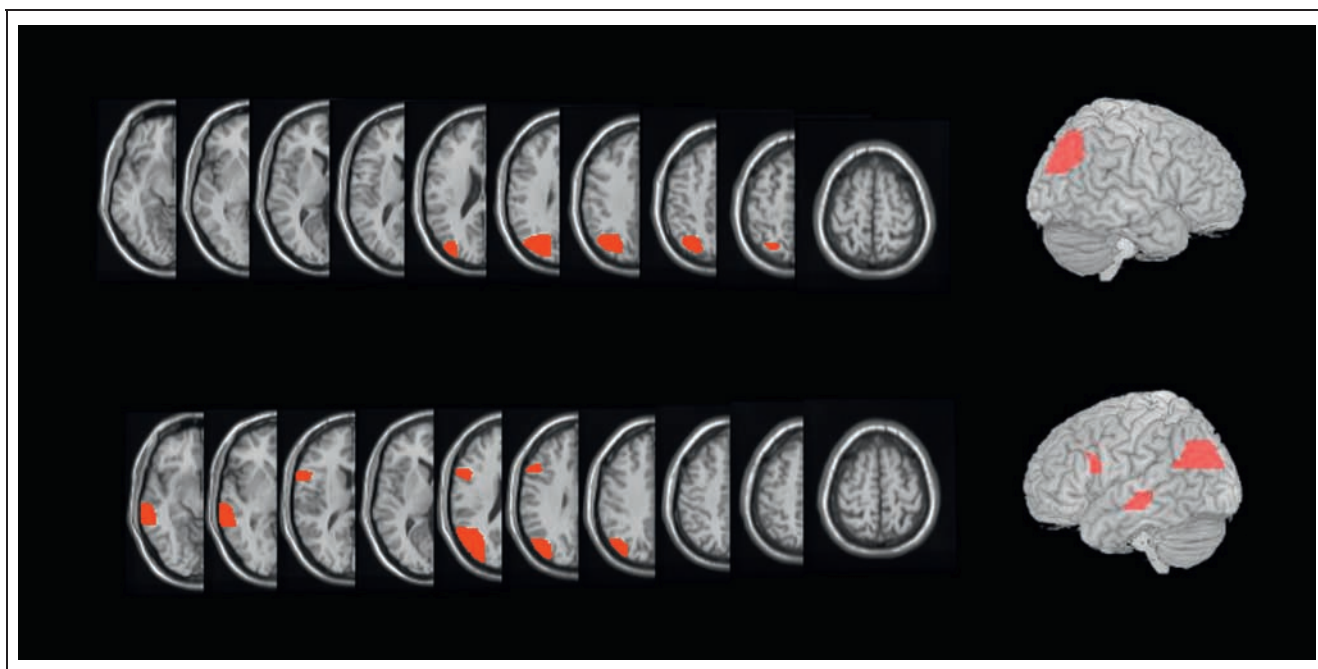


Figure 1. Reconstructions of K.E.'s right and left hemisphere lesions.

He correctly read 58% (46/80) of the words from Subtest 31 of the Psycholinguistic Assessment of Language Processing in Aphasia (Kay, Lesser, & Coltheart, 1992), often in a slow, laborious fashion. Twenty-five errors (74% of errors) were visually based (*church* read as “couch”), five (15%) were reports of one or more letters and four (12%) were omissions. On the latter trials, his attention appeared to be captured by irrelevant aspect

of the stimulus (e.g., the corner of the card) and he was unable to find the word. He read words of high imageability (e.g., “tablet”) better than words of low imageability (e.g., “effort”; 29/40 vs. 19/40), although the difference was not significant. Nonword reading was markedly impaired; he correctly pronounced only 3 of 50 four-letter nonwords. As has been reported in previous investigations of simultanagnosic subjects, many errors (66%) involved the report of one or more letters (Baylis, Driver, Baylis, & Rafal, 1994; Coslett & Saffran, 1991); he produced lexicalizations (*flig* read as “flag”) on 16 trials (34% of errors). Unlike several previously reported subjects (McCrea et al., 2006; Robertson & Treisman, 2006; Robertson et al., 1997), he did not produce errors in which letters in the array were reversed (e.g., *was* read as “saw”) or rearranged (e.g., *mean* read as “amen”).

K.E. reported only one of the overlapping figures for seven of the nine Ghent figures; for two stimuli he failed to identify any object. Despite being told that stimuli contained by a “big” and “small” letters, he reported only the small letter on 19/20 trials when shown hierarchical stimuli in which a single large letter was composed of a number of smaller, different letters (16); cf., Navon, 1977); on one trial he failed to report any letter.

K.E. generally performed well in identifying the orientation of a single stimulus (cf., Robertson & Treisman, 2006; Robertson et al., 1997). He distinguished inverted from upright faces perfectly on 20 trials. He made 2 errors on 20 trials in which he was asked to determine whether a letter was correctly oriented or mirror image reversed. He incorrectly accepted as correct a reversed “s” and “k.” Color processing was preserved; he named five different color patches (yellow, blue, red, green, or

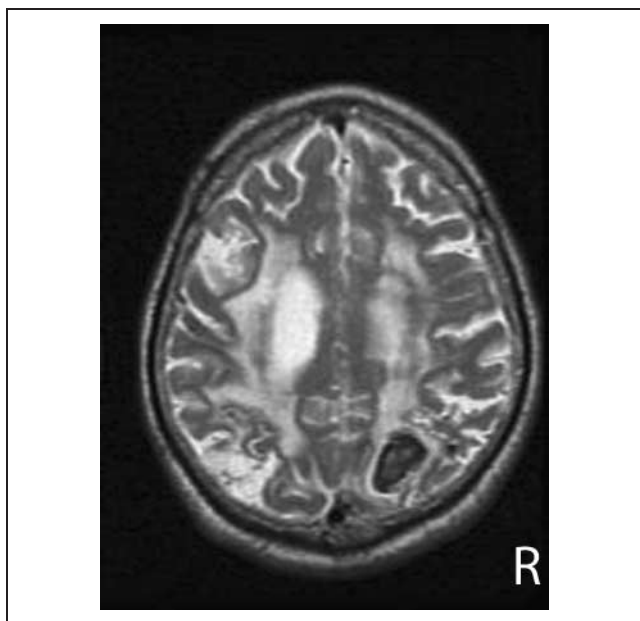


Figure 2. A high ventricular T2-weighted image demonstrating subcortical white matter abnormalities, a left parietal infarction and the residual effects of a right parietal intraparenchymal hemorrhage.

orange) accurately when presented individually in random sequence (30/30).

Finally, K.E.'s performance was influenced by the semantic category of the objects in the array. Like B.P. (Coslett & Saffran, 1991), he reported both items correctly significantly more reliably on trials on which both stimuli were drawn from the same semantic category (e.g., tools or animals) as compared to trials on which stimuli were drawn from different semantic categories; this was true for both pictures and words. Furthermore, as described in a separate manuscript (Coslett and Lie, in press), he exhibited profound repetition blindness with words, pictures, and letters. When presented an array containing different letters (e.g., "b n") he reported both letters correctly on 47% of trials, whereas he reported both letters correctly on same letter trials (e.g., "p p") on only 4% of trials.

Experimental Investigations

Methods are described below; unless otherwise stated, stimuli were presented on 12.7 × 17.8 cm blank white cards. Words and line drawings were either horizontally or vertically aligned and were separated by approximately 7 cm. Targets subtended approximately 2° of visual angle. Cards were presented in K.E.'s midline for an unlimited period. As noted below, other stimuli were presented on a monitor controlled by a Macintosh computer. We note that in preliminary testing, K.E.'s performance was quite similar with stimuli presented on cards or a computer monitor. Although he was more likely to report the right stimulus with horizontal (side by side) arrays and the top stimulus with vertical arrays (see below), overall performance with vertical and horizontal arrays was quite similar.

It should be emphasized that efforts were made to maximize performance on all tasks. K.E. was told that two stimuli were present on each card. On those trials on which only one target was reported, he was reminded that a second target was present and was encouraged to continue searching. He was given unlimited time on most tasks and consistently instructed to search for the second stimulus.

EXPERIMENT 1: PREATTENTIVE AND ATTENTION-REQUIRING VISUAL SEARCH

Experiment 1 was performed to assess K.E.'s visual search. The experiment was motivated by accounts that distinguish between "preattentive" and "attention-requiring" processes in visual perception (e.g., Treisman, 1998; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989; Treisman & Gormican, 1988). On Treisman's FIT, for example, visual features such as color and orientation are assumed to be processed in parallel in specialized cortical regions; visual attention, operating at the level of the Master Map of Locations, is assumed to be crucial for linking features

distributed across the different feature maps. On such an account, "preattentive" search for a feature such as the color red is fast and efficient because a response can be generated simply on the basis of activation at the appropriate feature map; that is, no linking of features is required.

Conjunction search, in contrast, requires attention because, in this instance, the relevant features are represented at multiple sites in the feature map; in order to determine whether a conjunction of the relevant features is present, the subject must not only register activity in the feature maps but also determine if the features are in the same location, a process that is assumed to require a limited-capacity interrogation of the master map of locations. Thus, the detection of a green "S" in an array of blue "X"s and red "T"s could be performed without spatial attention as the target is unique with respect to both color and form. In contrast, the detection of a red "T" in an array of red "S"s and green "T"s requires attention to determine if the features "red" and "T" are represented at the same location. Some (e.g., McCrea et al., 2006; Humphreys et al., 2000; Robertson et al., 1997; Friedman-Hill et al., 1995), but not all (e.g., Coslett & Saffran, 1991), simultanagnosic subjects produce illusory conjunctions in visual search tasks.

Methods

K.E.'s "preattentive" search was assessed by asking him to indicate if a green "S" was present in a nine-item arraying. On target present trials, there were four blue "X"s and four red "T"s in addition to the green "S." On target-absent trials there were either five blue "X"s and four red "T"s or four blue "X"s and five red "T"s. Each letter was 2 cm in height. Letters were randomly arrayed on 10 × 15.5 cm white cards. Cards were presented on a table in K.E.'s midline at a viewing distance of approximately 40 cm. Stimuli were presented until K.E. responded. There were 24 target-present and 24 target-absent trials presented in random sequence. The target was present in each quadrant of the card on six trials.

Attention-requiring search was assessed by asking K.E. to indicate if a red "T" was present in an array of red "X"s and green "T"s. On target-present trials there were four red "X"s and four green "T"s as well as the red "T." On target-absent trials there were either five red "X"s and four green "T"s or four red "X"s and five green "T"s. There were 24 target-present and 24 target-absent trials presented in random sequence. The target was present in each quadrant of the card on six trials. There were nine items in each array and a target was present on half of the trials.

Results

K.E. responded perfectly on 24 trials when the green "S" was present and made only one error on 24 trials

in which the target was not present (98% correct), suggesting that “preattentive” search was at least relatively preserved.

In the attention-requiring search, K.E. responded correctly on 21/24 (87%) target-present trials. He responded correctly on only 6/24 (25%) of target-absent trials. Overall, he responded accurately on 27/48 trials (56%), a performance that did not differ from chance. Additionally, he was as likely to report seeing a red “T” when it was absent as when it was present (18/24 vs. 21/24; Fisher’s Exact Test, $p = .4614$). Finally, although the data are not presented here in the interests of brevity, we note that array size was not critical; quite similar performance was obtained in a very similar visual search task involving five-item arrays.

Discussion

Although able to report the presence or absence of a single instance of a visual feature in an array quite reliably (98% correct), K.E. was at chance in judging if a target defined by the conjunction of visual features was present. In this respect, K.E. is similar to simultanagnosic patients reported by Robertson and colleagues (Robertson et al., 1997; Friedman-Hill et al., 1995), McCrea et al. (2006), and Humphreys et al. (2000).

One potential account of these data is that K.E.’s false alarms (reporting a stimuli that was not present) is attributable to a failure of the process that binds features processed in distinct cortical regions into a coherent perceptual unit (Treisman, 1998). Such an account was invoked to explain the presence of illusory conjunctions in another simultanagnosic (R.M.; Robertson et al., 1997; Friedman-Hill et al., 1995). We have recently proposed a closely related account for yet another simultanagnosic patient (McCrea et al., 2006) who produced frequent illusory conjunctions on a visual search task.

There is an alternative account of illusory conjunctions that should also be considered; if K.E. is unable to simultaneously perceive both attributes of the stimuli in Experiment 1—that is, shape and color—but responds on the basis of either letter shape or color alone, one would expect him to perform well on the “preattentive” task, in which the target is unique with respect to shape and color, but to produce false alarms on the attention-requiring task, in which the correct location of both attributes must be registered. Thus, if K.E. is unable to perceive object form (letter shape) and surface features of the stimulus (e.g., color), one would expect him to indicate that a target is present on both target-present and target-absent conditions as the target shape (“T”) is, in fact, present on both types of trials. On this account, illusory conjunctions would not reflect a miscombination of perceptual information but rather a failure to perceive all of the relevant visual features. This possibility, which was raised by preliminary clinical observations, was addressed in Experiments 2 to 4.

EXPERIMENT 2: REPORT OF WORD IDENTITY AND INK COLOR FOR COLOR WORDS

Data from Experiment 1 suggest that K.E.’s illusory conjunctions may not reflect the miscombination of visual information present in the array but rather the inability to perceive all of the visual attributes of the stimuli. If this were true, one would expect K.E. to be unable to report two attributes of the same object. This prediction was tested in Experiment 2, in which K.E. was asked to name a single written word and to name the color of the ink in which the word was written.

We note that this experiment differs in a crucial respect from most previous investigations of K.E. and other simultanagnosic subjects in which subjects are typically asked to report stimuli that differ with respect to locations. In those cases, the failure to report multiple different items in an array is readily interpretable as dysfunction in the mapping of spatial location. Asking K.E. to report two attributes of the same stimulus minimizes task demands with respect to the shift of attention or the integrity of spatial representations: Words can only be identified by virtue of processing the ink. The ability to name a word accompanied by a failure to name the color of the ink cannot be attributed to an inability to perceive the ink.

Methods

K.E. was shown letter strings consisting of four to seven letters and asked to name the stimuli. Letter strings were presented either printed on 12.7×17.8 cm white cards or on a monitor until K.E. responded. Letter strings were written in different color inks; in different blocks of trials, K.E. was asked to first read the word and then name the color or first name the color ink and then read the word.

In different testing sessions, two different types of stimuli were employed. First, the words red, blue, green, and yellow were employed. The words were presented in different color inks (red, blue, green, and yellow). Each word was presented in each color six times for a total of 96 trials.

A similar task was administered in which K.E. was asked to name six high-frequency nouns presented in red, yellow, green, and blue ink. The 24 stimuli were presented in random sequence on two occasions. On the first occasion, he was asked to name the word and then the color, whereas on the second occasion, he was asked to name the ink color and then the word. For both types of words, stimuli were presented with a monitor until he responded. He was always asked to name the color of the ink and the identity of the word while the stimulus was still in view.

In preliminary testing, K.E.’s ability to name the colors employed in the task was assessed by presenting 2.5×2.5 cm patches of the same colors in which the words were presented. Color patches were presented on a monitor until he responded. He named the color correctly on 36/36 trials.

Results

When asked to name the color words and then the color of the ink, K.E. correctly named the word on 47/48 trials; he always failed to name the ink color. When asked to name the color of the ink and then the word, he always named the word (48/48 correct) but never named the color. On all trials, K.E. explicitly stated that he did not see a color; he “assumed” that the words were written in black ink but stated that he did not recall seeing black ink (Table 1).

Data from high-frequency nouns were similar. Collapsing across the two sessions, he correctly named 30/48 (63%) of the words; on only two occasions, both when asked to name the color first, did he report seeing a color. He named the color as well as the word correctly on those trials. On 46/48 trials, he insisted that no color was present and said the words “must be in black.” Most reading errors were visually based (e.g., HOUSE read as “hose”). It should be noted that he was always asked to name the color of the ink while the stimulus was still present. His inability to name the color of the ink, therefore, cannot be attributed to a failure of memory.

Discussion

K.E. consistently reported the name of the word whether instructed to name the word or the color in which it was presented. Critically, on only two of 144 trials did he acknowledge that a color was present. This performance is consistent with the hypothesis that K.E. was able to “see” only one attribute of the object. The implications of these findings will be discussed below.

When instructed to name the color of the ink in which the word was written, K.E. continued to report the word; as he was perfect on a control condition in which he was simply asked to name color patches, we believe that his failure to report the color reflected the fact that naming the word is more automatic than identifying the color of the ink. We sought to address this possibility in the following experiment in which stimuli without a prepotent response were employed.

EXPERIMENT 3: NAMING TWO ATTRIBUTES OF A FORM

Methods

Stimuli for the experiment included four objects generated by crossing the variables of shape (circle, square) and stripes (present/absent; see Figure 3). Circles were 2.5 cm in diameter and squares were 2.5 × 2.5 cm. The

Table 1. Two Attributes of One Object: Words

	<i>Name Ink Color</i>	<i>Read Word</i>
Color words	0% (0/96)	99% (95/96)
High-frequency words	4% (2/48)	63% (30/48)

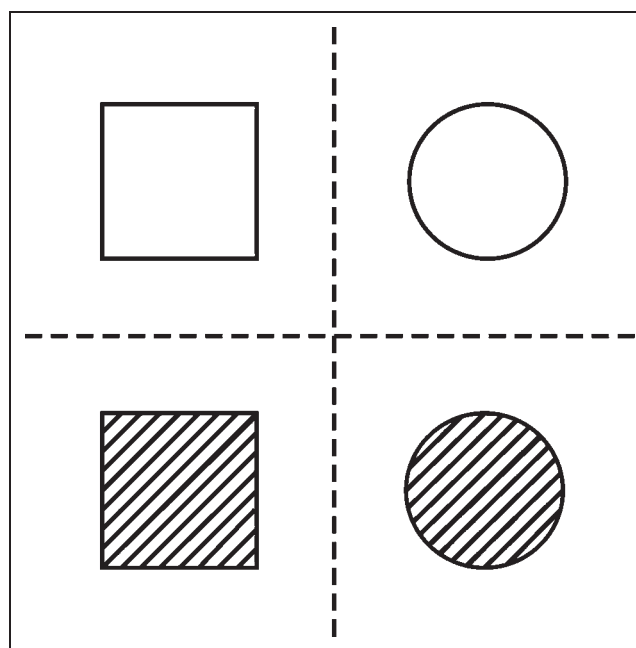


Figure 3. The four stimuli employed in Experiment 3.

contours and stripes were drawn with approximately 2-mm-wide lines on a 12.7 × 17.8 cm white card.

On 32 trials, K.E. was asked to name the stimulus shape and then to indicate if stripes were present; on another 32 trials, he was asked to indicate if stripes were present and then to state the shape of the stimulus. On all trials he was asked to name both the shape of the stimulus and whether the stimulus had stripes or not while the stimulus was in view. Stimuli were presented in 4 blocks of 16 randomized trials using an ABBA design, in which the order of report for shape and stripes was counterbalanced. All blocks of trials were administered the same day. Stimuli were in view while K.E. attempted to name the shape and indicate whether stripes were present.

Results

When asked to name the shape first, K.E. named the shape correctly on 31/32 trials; on one trial he correctly indicated that stripes were present but denied seeing a shape. When asked to first indicate if stripes were present, he responded accurately regarding the presence or absence of stripes on 32/32 trials but named the shape correctly on only two trials. Thus, he reported both attributes correctly on only 2/64 trials. He correctly reported the perceptual feature that was to be reported first on 63/64 trials, whereas he reported the perceptual feature to be reported second on only 3/64 trials.

K.E. was explicitly instructed to indicate the shape as well as the presence or absence of stripes on all trials. He clearly understood the instructions as indicated by his ability to verbalize the task demands and the fact that

on two trials he was able to report both attributes. On this and other tasks, K.E. was encouraged to guess on most trials; he was quite reluctant to do so, typically saying “that’s all I see.”

Discussion

Once again, K.E. was able to report only one attribute of a visual stimulus on the vast majority of trials. In contrast to Experiment 3, there was no prepotent response with these unfamiliar stimuli; K.E. reported the attribute to be attended first on 98% of trials. Thus, in this experiment, the visual attribute that K.E. reported was influenced not by the perceptual salience of the attribute but by task demands. Once again, however, the fundamental deficit appears to be the inability to direct attention to more than one visual attribute at a time or the inability to shift from one type of visual representation to another.

If K.E. “saw” only one feature of the stimulus, one might expect him to name the attended feature well but to perform at chance (50% correct) with respect to the second feature. K.E. performed significantly worse than chance when naming the second attribute; his errors on this and other tasks on which he was asked to report two attributes of a stimulus were omissions. We attribute this to K.E.’s reluctance to guess. As in the previous experiment, he was asked to report both stimulus shape and whether it had stripes while the stimulus was in view; his deficit cannot be attributed to a failure of memory.

EXPERIMENT 4: REPORT OF TWO ATTRIBUTES OF AN AUDITORY STIMULUS

This experiment was performed to address the possibility that K.E.’s failure to report both attributes of a stimulus reflected either a failure to understand the task requirements or an impairment in other processing domains (e.g., working memory). To address this issue, K.E. was asked to report two attributes of an auditory stimulus.

Methods

Fifty-six sentences of four to eight words were read aloud by either a male or female examiner standing behind the patient. K.E. was asked to repeat the sentence and then to indicate the gender of the speaker. Sentences were randomized with respect to gender.

Results

K.E. repeated all sentences accurately. Of greatest significance in this context, K.E. reported the gender correctly on 79% (44/56) of trials. Despite the fact that attempts were made to use gender-neutral sentences (e.g., “sew”

and “threw” were not used), most errors appeared to reflect the influence of gender stereotypes. Thus, he tended to respond “male” to sentences dealing with action. The task was administered to two age-matched normal controls; one subject performed perfectly, whereas the second subject made one error (98% correct).

Discussion

K.E. performed abnormally on the task, erring on 21% of trials on a task in which normal subjects were at ceiling. Nonetheless, it is clear that K.E. was substantially more accurate on this task (79% correct) than on tasks on which he was asked to report two attributes of a visual stimulus (3% correct in Experiment 3). There are several possible explanations for these data. One possibility is that K.E. suffers from a modality-independent deficit in processing two attributes of any stimulus. Although a modality-independent attentional “bottleneck” that precludes the report of more than one attribute of any stimulus cannot be definitively excluded, we believe that it is unlikely to be the primary deficit causing K.E.’s dramatic impairment as it does not account for the discrepancy with visual as compared to auditory stimuli. Furthermore, it is unlikely that the striking discrepancy in performance with visual as compared to auditory stimuli is attributable to differences in task demands. Whereas both tasks were regarded as quite easy by control subjects, controls judged the task from Experiment 4 to be more difficult because it required one to attend at the time of stimulus presentation and hold on to the information until ready to respond.

We contend that K.E.’s deficit demonstrated in Experiment 4 is consistent with our hypothesis that he is unable to bind information computed in the ventral and dorsal visual systems. In previous work we have demonstrated that performance on tasks that appear to have no explicit spatial dimension—for example, language—may be influenced by spatial factors (Coslett, 1999; Coslett, Schwartz, Goldberg, Haas, & Perkins, 1993; see also Lie, McCrae, & Coslett, 2006). On the basis of these data, we argued that stimuli with no apparent spatial dimension are marked for location; furthermore, we argued that a disruption of the binding of this location information to language and other sensorimotor systems may underlie these spatial effects (Coslett, 1999). Thus, K.E.’s impairment in the report of both attributes of an auditory stimulus may reflect a failure to bind location information to language systems.

Finally, the fact that K.E. reported both attributes on 79% of trials strongly suggests that his failure to do so on tasks involving visual stimuli is not attributable to a failure to understand task demands. We note that this conclusion was supported by data from another experiment that are not presented in detail for the sake of brevity. K.E. was asked to imagine that he was looking at an object and to report both its color and relative size (“Is it

larger than a softball?’). He answered both questions correctly for 15/16 objects, demonstrating that his impairment on the tasks described above cannot be attributed to a failure to understand the task, impaired working memory, or loss of knowledge of object attributes.

Discussion of Experiments 2 to 4

Data from the preceding three experiments demonstrate that K.E. was unable to report more than one attribute of a visually presented object. Thus, what appear to be illusory conjunction errors reflecting the miscombination of features in the array (e.g., the color red and the form “T”) may be attributable to the inability to consciously register both visual features rather than a deficit in the binding of low-level visual information.

In this context, K.E.’s relatively normal object recognition is relevant. If K.E. suffered from a low-level deficit in the binding of visual feature information, one would not expect him to identify visually presented stimuli as this process necessarily entails the integration of visual feature information computed in early visual cortices. In order to accommodate this apparent paradox, Shalev and Humphreys (2002) and Cooper and Humphreys (2000) suggested that the ventral and dorsal systems differ with respect to the manner in which spatial information is employed: The former computes spatial relations between the features of a candidate object, whereas the latter computes the spatial relations between candidate objects. This account does not eliminate the binding problem but rather defers it; the visual system must ultimately integrate information about object identity and location. Thus, we suggest that K.E. suffers from an impaired ability to bind visual information but that the impairment arises at a stage of processing after which visual feature information is integrated. More specifically, we contend that K.E. is unable to link object identity and other stimulus attributes computed in the ventral visual system to the spatial representations computed by the dorsal visual system.

The striking impairment in the ability to report more than one attribute of a visual display exhibited by K.E. argues that the linking of visual information computed in the dorsal and ventral visual streams is a limited-capacity operation. The hypothesis that K.E.’s bilateral posterior parietal lesions caused a pathologic reduction in the resources necessary for the binding of information computed in the dorsal and ventral streams may take at least two closely related forms. On one account, the critical deficit underlying K.E.’s simultanagnosia is the number of linkages that can be maintained between information computed in the ventral stream to spatial representation computed in the dorsal visual stream. Thus, K.E. may be able to sustain only one linkage, unless there is top-down support that reduces the binding resources required. Consistent with the claim that top-down support plays an important role in K.E.’s performance, on

tasks described elsewhere (Coslett & Lie, in press), K.E. exhibited an effect of object identity on report of two-item arrays. He was significantly more likely to report semantically related items but failed to report both items if they were identical (repetition blindness).

Another possible explanation of K.E.’s performance is that he is slow in disengaging from one type of representation and shifting to another. Data suggesting that subjects with neglect (Ptak & Schneider, 2006; Posner, Walker, Friedrich, & Rafal, 1984) and simultanagnosia (Pavese, Coslett, Saffran, & Buxbaum, 2002) may be impaired at disengaging attention from one location to shift to another location have been reported by several investigators. One might argue that K.E. also exhibits a disengage deficit of a somewhat different type—that is, unlike previous subjects who were impaired at disengaging attention from a location, K.E. may be unable to disengage from one type of representation (e.g., color) to shift to another type of representation (e.g., shape). On this account, the ability to report two attributes of an object may not require that multiple representations be simultaneously linked to a spatial representation but rather that the system be able to shift quickly and efficiently from one linkage to another. This distinction may be illustrated by considering Experiment 4, in which K.E. was asked to report both the stimulus shape and whether stripes were present. On the first account, K.E.’s inability to report both the shape and the presence/absence of stripes would reflect an inability to simultaneously bind the shape to a location while also binding the stripes to a location. On the disengage account, the deficit would be attributable to the fact that, once having directed attention to a particular attribute of the stimulus (e.g., shape), he is unable to shift attention to process another attribute of the stimulus (e.g., stripes). We recognize that these accounts are closely related and not mutually exclusive.

Finally, data from Experiments 2 and 3 strongly argue that K.E.’s deficit is not a failure to register visual information or a failure of top-down control of visual processing. As noted above, he was unable to report the color of the ink that formed the word; as the ink itself constituted the stimulus, his failure to report the color cannot be attributed to a failure to perceive the colored ink. K.E.’s performance on the stripes absent condition of Experiment 3 is relevant with respect to the question of the top-down control of visual processing. K.E. performed perfectly when asked to report whether stripes were present when presented either a circle or square without stripes. That is, when asked to attend to the stripes, he correctly reported their absence but was then unable to “see” the shape. The fact that he did not simply report stimulus shape on these trials suggests that, even in the absence of the relevant stimulus, visual attention was not captured by the visual stimulus that was present; in this regard, K.E. is quite different from other subjects with simultanagnosia who appear to be

unable to control the location in space to which attention is allocated (cf., Pavese et al., 2002).

The hypothesis that K.E.'s inability to report more than one object or more than one attribute of the same object is attributable to a failure to bind information computed in the ventral, object recognition systems with location information computed in the dorsal stream makes a specific prediction regarding the role of unreported information. This account assumes that processing in the ventral stream is preserved. On this account, one would expect visual information regarding object identity and other stimulus attributes, such as color, to be adequately represented even if not reported. If this is the case, one might expect this information to influence performance despite the fact that the information is not available for report. We explored this possibility in a series of three experiments.

EXPERIMENT 5: PROCESSING OF UNREPORTED INK COLOR

A variation of the Stroop test was performed in which K.E. was asked to read aloud color words written in the same (congruous) or different (incongruous) color.

Methods

The four color words and the ink colors described in Experiment 3 were used (red, blue, green, yellow in both instances). Eight blocks of 48 trials were prepared; in each block, 24 stimuli were color congruent and 24 were incongruent. For each word, the time from stimulus presentation to naming was recorded by the examiner; the examiner depressed the space bar of a keyboard as soon as K.E. responded. (A voice-activated relay was considered impractical because of K.E.'s tendency to vocalize prior to responding.) The examiner could not see the monitor and was therefore blinded with respect to the accuracy of response. Sessions were tape recorded for later scoring of accuracy. Four blocks were administered in each of two sessions 1 week apart.

Results

K.E. read both congruous and incongruous color words accurately (99% and 97% correct, respectively). Seven of eight errors involved misreading the word "yellow" as "follow"; six of the seven errors were on incongruent trials. For each block, mean RTs for correct trials for both the congruous and incongruous trials were calculated. Although, as in Experiment 2, K.E. never acknowledged seeing a color, RTs on incongruous trials were significantly longer than on congruous trials [2190 ± 602 msec. vs. 1720 ± 293 msec; $t(7) = 3.32, p = .006$]. The implications of these data will be discussed below.

EXPERIMENT 6: PREFERENCE FOR CONGRUOUS WORDS

To further explore the extent to which unreported perceptual attributes influenced performance, a forced-choice task was administered in which K.E. was not required to explicitly name any attribute of the stimulus but simply to indicate which of two exemplars was "better" or "preferable."

Methods

Stimuli included the four color words used in Experiment 3. On each trial, the color word was presented twice, once in the congruous ink and once in an incongruous color. Each word was presented seven times. Words were horizontally aligned on 13×17 cm cards. The congruous exemplar was on the right on half of the trials. K.E. was asked to indicate which of the exemplars he "preferred" or was "better." After responding he was also asked to identify the ink color of the stimuli. This experiment was administered 6 weeks after the task described in Experiment 2.

Results

Although he explicitly denied seeing the ink color on all trials and was utterly unable to explain his selection, he "preferred" the congruous stimulus on 22/28 trials, a performance that is substantially higher than chance ($p < .01$). On five trials in which he preferred the incongruous stimulus, the stimulus was on the right. He never reported the color of the ink, always stating that the words were presented in "black."

EXPERIMENT 7: NAMING OF COLORED LINE DRAWINGS

This experiment was performed to determine whether the color of an object influenced naming of line drawings. We note that in preliminary testing in which K.E. was asked to name appropriately colored line drawings and then their colors, he named the objects correctly on approximately 85% of trials but named the color of the drawing on only approximately 50% of trials. Thus, K.E. demonstrated a substantial deficit in the processing of the color of an object despite the fact that he performed well in object identification. The interpretation of these data was complicated by the fact that many common objects have a strong color association (tomatoes are red, lemons are yellow, etc.). Thus, it was unclear whether K.E. perceived the color of the object or responded on the basis of stored knowledge of the color of objects.

In order to assess whether K.E. was able to perceive both the identity and color of line drawings he was asked to name appropriately (e.g., a yellow lemon) and inappropriately colored objects (e.g., a blue lemon). We

reasoned that if K.E. failed to perceive the color, there would be no difference in object naming as a function of color. In contrast, if the color of the stimulus was perceived, he would be more likely to name the appropriately colored object.

Methods

Twenty-four line drawings of common objects drawn from the Snodgrass and Vanderwart (1980) corpus as well as the Boston Naming Test served as stimuli. Two versions of each object were prepared. One was generated by hand-coloring the 24 items in a naturalistic color, whereas the second exemplar was colored in an unnatural manner. Two blocks of stimuli were generated, each of which contained 12 appropriately and 12 inappropriately colored items. Each item occurred once in each block of stimuli. Line drawings were pasted onto 13 × 17 cm cards. Items were presented in K.E.'s midline until he responded. Blocks of stimuli were presented 1 week apart. K.E. was asked to name each item.

Results

K.E. named appropriately colored items significantly more reliably than inappropriately colored items (19/24 vs. 7/24; Fisher's Exact Test, $p = .0012$). After the blocks of trials were administered, K.E. was asked if he noticed anything unusual about the color of the stimuli; he stated that he did not remember seeing any colors.

Discussion

In experiments employing both words and line drawings of common objects, K.E.'s performance was influenced by a stimulus attribute of which he was unaware. This finding is consistent with the hypothesis that K.E.'s impairment is not in the registration of visual feature information but arises at a "higher" level. At least for K.E., we suggest that the deficit represents a restriction in binding visual information to spatial representations and, as a consequence, a failure of awareness.

GENERAL DISCUSSION

K.E. exhibited profound simultanagnosia and optic ataxia in the context of bilateral parietal lobe lesions (as well as white matter hyperintensities). Although he reported "illusory conjunctions" of color and form in Experiment 1, subsequent experiments demonstrated that he was not only unable to reliably identify more than one stimulus in an array but was also unable to report more than one attribute of a single stimulus. These findings suggest that apparent illusory conjunctions were attributable to an inability to consciously process more than

one attribute of a stimulus rather than the miscombination of two stimuli present in the array. Finally, we demonstrated in a series of experiments that the perceptual attributes that K.E. was unable to report were, in fact, perceived. We suggest that K.E.'s performance has important implications for accounts of normal visual processing and the relationship between the "what" and "where/how to" systems. First, these data suggest that the conscious perception of arrays is crucially dependent on a limited-capacity procedure by which information computed in the "what" and "where/how to" systems is linked. Disruption of this limited-capacity binding system, we suggest, causes K.E.'s simultanagnosia.

On this account, the procedures by which objects are recognized are at least relatively preserved. Consistent with this claim, K.E. reliably recognized familiar objects and words for which substantial top-down support is available. We recognize that K.E.'s impairment in recognition of unfamiliar stimuli (e.g., nonwords) represents one potential objection to the claim that the ventral system is preserved. The resolution of this apparent paradox comes from an appreciation of the relative roles of the dorsal and ventral stream in object recognition. As has been argued by a number of investigators (McCrea et al., 2006; Robertson & Treisman, 2006; Humphreys et al., 2000; Humphreys & Riddoch, 1995), the dorsal and ventral visual systems differ fundamentally with respect to the spatial relations they compute. Whereas the dorsal system appears to compute the relations between objects, probably in an egocentric spatial coordinate system, the ventral system generates a spatial representation in which the relations between elements of the object are represented (Robertson & Treisman, 2006; Humphreys et al., 2000).

Stored representations for familiar objects are likely to facilitate the computation of the relationships between elements of an object. In contrast, unfamiliar stimuli are likely to be segmented by early visual processes into multiple discrete elements. The dorsal visual system is crucial for the computation of the relationship between the relatively discrete elements. For example, for nonwords there is no stored word form information to facilitate the computation of the relationships between elements of the stimulus; as a consequence, the nonword may be perceived as a series of discrete elements rather than a single unit. As the computation of the relationships between discrete elements in a manner that can contact the ventral stream is regarded as a crucial element of simultanagnosia by many investigators (Robertson, 2003; Humphreys et al., 2000; Robertson et al., 1997), we suggest that his deficit in recognition of unfamiliar stimuli is not inconsistent with the view that the ventral processing stream is relatively preserved.

Although a disruption of the dorsal system with a loss of spatial information may represent the fundamental deficit in many subjects with simultanagnosia (cf., McCrea

et al., 2006; Robertson et al., 1997), we suggest that K.E.'s deficit cannot be adequately explained on this basis for a number of reasons. First, the apparent absence of true illusory conjunctions is consistent with the hypothesis that the initial coding of spatial location is relatively preserved; we note that the presence of illusory conjunctions has been taken by many investigators as evidence of a loss of the ability to mark the location of visual information (McCrea et al., 2006; Humphreys et al., 2000; Robertson et al., 1997). Second, it is not clear that a loss of spatial information would give rise to K.E.'s most striking and, to our knowledge, heretofore unreported deficit, an inability to "see" more than one attribute of the same object. Thus, K.E. is unable to both name a word and report the color ink in which the word was presented despite the fact that the ink constitutes the word. The mechanism by which loss of spatial information would lead to a failure to report one of the stimulus attributes is not clear.

Finally, the demonstration that K.E.'s performance is influenced by semantics is also relevant. Given the hierarchical but highly interactive nature of the visual system, one might expect stored information regarding an object's shape or form to at least partially compensate for a deficit in the precision with which visual features are registered, thereby facilitating object/word recognition. The semantic effects on two object arrays, however, are not readily attributable to such a facilitation. Indeed, we (Coslett & Lie, in press; Coslett & Saffran, 1991) and others (Ptak & Schneider, 2005) have argued that the effects of semantic relatedness on report of two items in an array demonstrate that the objects have been processed to a high level. Thus, the fact that K.E. reports both items more reliably when shown a pig and a bear as compared to a pig and a hammer suggests that both stimuli contact stored information regarding object form and identity.

IMPLICATIONS FOR AWARENESS

We have argued that K.E.'s inability to "see" more than one object or more than one attribute of the same object is not attributable to a deficit in the processing of visual feature information, the integration of visual feature information into structural descriptions, or an inability to mark the location of visual percepts but instead reflects a pathologic restriction in the ability to bind information computed in the dorsal and ventral visual systems. Implicit in this account is the assumption that the ability to report perceptual attributes requires that those attributes be linked to information specifying the location of the stimulus. Several lines of evidence support this claim.

In a review of behavioral and imaging studies of the neural basis of awareness, Kanwisher (2001) concluded that the binding of activated perceptual attributes with a representation that specifies the time and place in which

a stimulus appears is a necessary prerequisite for awareness. Additionally, studies of subjects with brain lesions support this contention (Coslett, 1999; Berti & Rizzolatti, 1992; see Driver, Vuilleumier, Eimer, & Rees, 2001; Rees et al., 2001 for reviews).

The loci of K.E.'s lesions are also of relevance in this context. Although conclusions regarding the anatomic basis of K.E.'s deficit must be tempered by the presence of generalized white matter increased signal and the presence of small left frontal and temporal infarctions, K.E.'s simultanagnosia was, we believe, primarily attributable to the bilateral posterior parietal lesions involving the angular gyrus. These lesions were not only the most extensive of his infarctions but simultanagnosia was first noted at the time of the right parietal hemorrhage. Studies of the anatomy of the inferior parietal cortex are consistent with its putative role in binding location information and object identity. For example, Watson, Valenstein, Day, and Heilman (1994) suggested that the inferior parietal cortex represents the human analogue of the monkey temporal polysensory cortex that, when damaged, gives rise to neglect. In the same vein, Boussaoud, Ungerleider, and Desimone (1990) argued that the superior temporal polysensory region should be regarded as a component of a "third stream" as it is interconnected with both dorsal and ventral streams (see also Milner & Goodale, 1995). Rizzolatti and Matelli (2003) recently argued that the dorsal stream should be divided into the "dorsal dorsal" and "ventral dorsal" systems with the latter being crucial for skilled action and action recognition. Broadly consistent with this view, Buxbaum, Kyle, and Menon (2005) recently proposed the "Two Action System" according to which the inferior parietal lobule, by virtue of its reciprocal connections between the superior parietal lobule and the temporal lobe, serves to integrate spatio-motor information with object knowledge to generate skilled hand-object interactions. Finally, Fridman et al. (2006) have argued for a dorsal-ventral gradient in the parietal lobe, such that meaning and memory assume a greater role in the representations computed by the parietal lobe as one approaches the ventral stream. In summary then, a number of lines of evidence are consistent with the view that the inferior parietal lobule is crucial for the binding of the dorsal and ventral streams, perhaps by virtue of generating representations in which object location and identity are indexed.

We do not claim that K.E.'s visual system lacks information regarding the location of visual stimuli and even objects. Several investigators have reported simultanagnosic subjects who exhibited implicit knowledge of object location but were at chance in reporting the location of stimuli that they had identified (Humphreys & Riddoch, 2003; Robertson et al., 1997). As suggested by Humphreys and Riddoch (2003) (see also Heinke & Humphreys, 2003), implicit knowledge of the location of objects may reflect interactions between object-

and space-based representations in early visual cortices. The inability to offer explicit information about object identity, attributes, or location in patients with simultanagnosia reflects, we suggest, a failure to link spatial representations computed in the parietal lobe to information about object identity and perceptual attributes computed in the temporal lobe.

A final issue concerns the implications of the data from K.E. for the syndrome of simultanagnosia. Balint (1909) attributed the disorder to impaired visual attention. He emphasized that his patient's visual fields were full, suggesting that the deficit was not readily attributed to a failure to register visual information. Many subsequent investigators have suggested that simultanagnosia is attributable to impaired visual attention (Humphreys et al., 2000; Robertson et al., 1997; Holmes & Lister, 1916). Consistent with this thesis, a number of patients have produced illusory conjunctions on visual search tasks (McCrea et al., 2006; Humphreys et al., 2000; Robertson et al., 1997; Friedman-Hill et al., 1995) or demonstrated difficulties disengaging attention (Pavese et al., 2002; Verfaellie & Heilman, 1990).

Although we agree that there is compelling evidence that simultanagnosia may be associated with deficits in visual attention in many subjects, we suggest that this account does not adequately explain the performance of at least some subjects with simultanagnosia. We reported a simultanagnosic patient (B.P.) with bilateral lesions involving the posterior parietal and superior temporal lobes (Coslett & Saffran, 1991). B.P. did not produce illusory conjunctions on any task. Additionally, she exhibited at least relatively normal performance on a task assessing the ability to shift visual attention (Posner et al., 1984), demonstrating that she did not manifest a "disengage" deficit. Like K.E., she was significantly more likely to report both items in an array if they were semantically related. We argued that B.P. was unable to link information regarding object identity to an egocentrically defined location.

Based on the data from K.E. as well as B.P. (Coslett & Saffran, 1991), we suggest that at least two broad subtypes of dorsal simultanagnosia may be identified: one characterized by an early visual attention impairment and a second in which the disorder primarily reflects a later impairment in binding information computed in the dorsal and ventral visual streams (Coslett & Chatterjee, 2003). Furthermore, although the anatomic data must be interpreted with caution because the relevant lesions are large and asymmetric and the number of patients is small, lesion overlaps suggest that the behavioral distinction was associated with a dissociation in the lesion sites. Both patients with "binding deficit" simultanagnosia exhibited lesions involving the inferior parietal lobes bilaterally (e.g., Brodmann's areas 39, 40), whereas both patients with simultanagnosia secondary to visual attention impairment exhibited lesions involving the superior parieto-occipital junction bilaterally

(see Coslett & Chatterjee, 2003 for figures). Data from other well-studied patients with simultanagnosia appear to be consistent with this distinction as well. Humphreys and Riddoch (2003), Shalev and Humphreys (2002), and Humphreys et al. (2000) reported a patient, G.K., whose lesion on the right side involved the occipital lobe. Patient R.M. studied extensively by Robertson and Treisman (2006) and Robertson et al. (1997) involved the lateral occipital cortex (Brodmann's area 19) bilaterally as well as portions of the posterior parietal cortex.

Reprint requests should be sent to H. Branch Coslett, Department of Neurology, University of Pennsylvania School of Medicine, 3400 Spruce St., Philadelphia, PA, 19104, or via e-mail: hbc@mail.med.upenn.edu.

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