

# CAN DEFICITS IN SPATIAL INDEXING CONTRIBUTE TO SIMULTANAGNOSIA?

---

**B. Laeng and S.M. Kosslyn**

*Harvard University and Massachusetts General Hospital, Cambridge, USA*

**V.S. Caviness and J. Bates**

*Massachusetts General Hospital, Cambridge, USA*

Patient AMA suffered a head trauma that left her with several visual complaints, including a reading disability. AMA appears to suffer from simultanagnosia, as established with tasks such as naming briefly presented multiple stimuli or overlapping figures, describing the theme of complex scenes, and counting arrays of stimuli. Specifically, AMA has difficulty perceiving immediately successive stimuli and, in particular, multiple stimuli that appear at novel or unexpected locations. Her ability to encode spatial relations rapidly (of either the categorical and coordinate type) is markedly reduced. However, when a familiar target appears among multiple stimuli at expected (previously encoded) locations, AMA's performance can be within normal limits. These results suggest that this patient's simultanagnosia cannot be reduced to an inability to process multiple stimuli *per se*. Rather it is better characterised as (1) an inability to index new locations of multiple stimuli, and (2) a reduced efficiency in pattern analysis. The former deficit, in turn, may lead to difficulty in focusing on objects efficiently and using objects as landmarks or reference points. Damage to one or both of the above mechanisms could produce simultanagnosia and reading difficulty.

## INTRODUCTION

Following brain damage, some patients are able to perceive only a single object at a time. This disorder has been named *simultanagnosia*. Although the etymology may suggest that the hallmark of the disorder is a problem with simultaneity, the critical variable may be that multiple visual stimuli appear within a brief period of time (typically a second or less). These patients are reported to have difficulty in recognising and identifying multiple dispersed or

overlapping objects (e.g. Bálint, 1995; Luria, 1959) when they are presented simultaneously or serially (but rapidly; e.g. Kinsbourne & Warrington, 1962). Such patients can also have difficulty in identifying single objects that have multiple parts, especially when the parts can be identified as separate objects. For example, some simultanagnosics have difficulty reading words, which is manifested in a laborious letter-by-letter reading strategy. Because reading can be a clear expression of the pathology, several simultanagnosics have been

---

Requests for reprints should be addressed to Bruno Laeng, PhD, University of Tromsø, Department of Psychology, Åsgårdveien 9, 9037 Tromsø, Norway (Tel: (+47) 77 64 63 6728; Fax: (+47) 77 64 52 91; E-mail: bruno@psyk.uit.no).

The authors are profoundly grateful to AMA for being so patient with many abstruse tasks, and for her enthusiasm. We thank Glyn Humphreys and three anonymous reviewers for invaluable help, and Charlie Butter, Alfonso Caramazza, and Michele Miozzo for useful criticisms and advice. We are also grateful to Carolyn Rabin for her help in testing some of the control subjects.

During this study Bruno Laeng was supported by a JSMF grant (No. 94-34) from the James S. McDonnell Foundation and The Pew Charitable Trusts; Stephen Kosslyn was supported by grant NINDS 3P01 17778-09; and Verne Caviness and Julie Bates were supported by program project grant 5P01 NS27950-04.

thoroughly examined on visual tasks that used exclusively alpha-numeric symbols (i.e. strings of digits, letters, words; e.g. Levine & Calvanio, 1978).

Phenomenologically, these patients report that their visual consciousness is composed of sequences of singular contents, which may fail to be integrated into a meaningful whole (e.g. Coslett & Saffran, 1991). This disjointed and narrow awareness is evident in early descriptions of these patients' attempts to understand the meaning of depictions of complex scenes (Wolpert, 1924; cf. Weigl, 1964). Such scenes or thematic pictures seem to become meaningful for the patients only after effortful piecemeal examinations (see Paterson & Zangwill, 1944; Williams, 1970), which are abnormally slow, characterised by much guessing, and often fail to capture the meaning or theme of the ensemble.

It is likely that damage that disrupts any of several cognitive mechanisms could produce simultanagnosia. Indeed, a family of theoretical accounts exists for this syndrome; some of these accounts focus on the disruption of a specific process (e.g. the speed of a mechanism), and others focus on the disruption of a representational structure. In this article, we also propose a new account, which is cast at a relatively low level of processing. We assume that different disruptions of a processing system can sometimes result in similar pathological expressions (e.g. see Kosslyn & Koenig, 1995). Indeed, it seems likely that different types of simultanagnosia exist, and hence we take it as one of the goals of contemporary cognitive analyses to make the traditional taxonomies (often based on "common sense") more precise and illuminating. Farah's (1990) distinction between a "ventral" and a "dorsal" simultanagnosia (each taking its name from that of a major visual stream, which are concerned, respectively, with the perception of objects' shapes and locations) is a first step in this direction.

In the following part of this section we present several alternative hypotheses that have emerged in the neurological/neuropsychological literature as viable accounts of simultanagnosia. The first three accounts are centred on deficits of mechanisms of focal attention. The other two are centred on deficits in perceptual mechanisms that analyse either spatial or shape information. At the end of the sec-

tion we present a sketch of a new model that may illuminate several aspects of the pathology.

## Restricted Visual Attention

One of the oldest accounts of simultanagnosia rests on the notion that these patients have a restricted field of attention. This hypothesis dates back at least to Bálint (1995, first published 1909) and Holmes (1919). Bálint observed that his patient could not simply have had a narrowing of the sensory field, because an object's size did not affect performance: Large objects could be clearly identified and described in some of their detail (e.g. a person and his clothing), but once the patient fixated on an object (e.g. a needle) the nearby objects would go unnoticed (e.g. a candle only 5cm away). Therefore, Bálint suggested that attention would always be as narrow as the size of the object under regard. In contrast, Thaïs and De Bleser (1992) reported a case who apparently had an actual restriction of the attentional window ("lens"), so that complex stimuli could be processed as wholes if they occupied a small visual angle, but only their parts could be recognised at relatively larger visual angles.

## Disengagement Difficulties

Patients with Bálint's syndrome seem to have an extreme form of spatial neglect, which is characterised by a loss of attentional shifts to stimuli peripheral to the one capturing the focus of attention (which is expressed as "sticky fixation" or "paralysis of gaze"). Bálint's cases suffer from bilateral parietal damage (see Hausser, Robert, & Giard, 1980; Rousseaux, Delafosse, Devos, Quint, & Lesoin, 1986), and damage to each superior parietal lobe individually often results in visual extinction (e.g. Posner, Walker, Friedrich, & Rafal, 1984). Thus, it can be argued that damage to both such areas causes a form of double contralateral neglect, or an "attentional disengaging" deficit (Allport, 1993; Farah, 1990; Kosslyn & Koenig, 1995). However, such neglect extends to all three dimensions; these patients also fail to report and orient to stimuli that are above/below or behind others (Williams, 1970). Farah has described this variety of simultanagnosia as a "dor-

sal" type because it arises following damage to the spatial system, which is implemented in the dorsally located areas of the occipital and parietal lobes of the brain.

### Slowed Visual Attention

Kinsbourne and Warrington (1962) suggested that simultanagnosia may result from slowed attentional processing. Influenced by Broadbent's (1958) early view of attention as a filter through which only one percept at a time can pass, they identified the speed of filtering as the fundamental difference between normal people and simultanagnosics. According to this view, the inability to shift attention rapidly from object to object leads the patient to experience seeing only one object at a time; in contrast, in normal perception, many objects can be apprehended at the same time because one shifts so quickly between successive stimuli that the percepts are integrated before they decay from short-term memory. Alternatively, the limitation of perception to a single element could be a serial strategy developed by the patient to cope with depleted attentional and/or perceptual resources (which otherwise would allow only poor and inadequate sampling of multiple stimuli). According to this reasoning, slowing is a secondary effect of attentional narrowing (see earlier) or impaired perceptual analysis (see following). The serial strategy leads attention to be focused on a more limited range of visual input so that, typically, only one object is chosen to be processed at one time. "One at a time" does not imply that all stimuli have to be physically present simultaneously: As predicted, such patients have difficulty processing stimuli presented in a rapid sequence (Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978).

### Deficient Spatial Mapping

Another possibility is that simultanagnosia occurs because the mechanisms that register spatial locations are impaired (Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997). In their computer model of high-level visual processing, Kosslyn, Flynn, Amsterdam, and Wang (1990)

showed that the model could simulate (coarsely) something like simultanagnosia when the "spatiotopic mapping" component of the model was damaged. The model's lesion forced it to assign the same location to all stimuli, which prevented it from identifying more than one object. Similarly to the patients, the model appeared to be "locked onto" an initial stimulus and did not "look for" other objects. Alternatively, the visual system may be able to switch attention from object A to object B but, because an identical spatial location is incorrectly assigned to both, once recognition of object A is completed, it "disappears" from sight to be substituted by object B. In both scenarios, the outcome is the same: The system is not capable of seeing more than one object at the same time.

Coslett and Saffran (1991) discussed a single case of simultanagnosia as resulting from an inability to maintain location information for more than one shape; in their account, this would lead the patient to seeing a single item at a time, because only one explicit "binding" can occur between spatial and shape information. Friedman-Hill, Robertson, and Treisman (1995) have also described a simultanagnosic patient with bilateral parietal lesions whose inadequate spatial representation of visual objects impaired the patient's ability to combine ("bind") colour and shape properties of objects. In this view, multiple explicit "object files" (cf. Kahneman, Treisman, & Gibbs, 1992) cannot be formed if multiple spatial and shape attributes cannot be integrated.

### Deficient Pattern Analysis

Another explanation posits that these patients have difficulty in analysing shape. According to this hypothesis, brain damage can cause the ventral system to slow down, possibly because those areas that compare input to stored visual representations cannot accept a second input until the first one is processed to a certain degree (Kosslyn & Koenig, 1995). Delays in shifting attention from object to object would be a secondary effect of this deficit in perceptual analysis. Luria (1959) offered a similar view, based in part on speculations by Pavlov, who suggested that the damage may cause a "weak-

ening" of the visual cortex so that it had to concentrate its activity at a single point. In Luria's view, the damaged visual areas would only be able to sustain the excitation of one, extremely unstable, stimulus trace. Consistent with this view, Rizzo and Hurtig (1987) reported cases in which visual stimuli fade from awareness when a simultanagnosic fixates on them. Levine and Calvanio (1978) also propose a similar account of simultanagnosia, and attribute the pathology to difficulty in discriminating among visual features. In general terms, this class of accounts revolves around the idea that the brain damage causes "feature degradation" or increased "noise" in the perceptual system. The sequential allocation of attention to parts of a scene or an object has the effect of increasing the signal-to-noise ratio (cf. Rapp & Caramazza, 1991).

Farah (1990) has characterised this variety of simultanagnosia as "ventral" simultanagnosia because it arises following disruption of the object recognition system, which is implemented in the ventrally located areas of the occipital and temporal lobes of the brain. Humphreys and Price (1994) have proposed that simultanagnosia can arise from deficits in representing form information (i.e. "parallel feature discrimination"), as suggested by two cases of simultanagnosia with abnormal performance in visual search tasks that normally result in "pop-out" effects and failure to encode a single shape at brief exposures. Rapp and Caramazza (1991) have also described a case with absence of "pop-out" effects in visual search tasks and a resulting letter-by-letter reading strategy (see also Kay & Hanley, 1991).

According to Humphreys and colleagues' account, simultanagnosia could be the result of either a problem in parsing (i.e. segmenting figure from ground), or, at a lower level, in discriminating elementary visual features (i.e. nonaccidental properties; see Lowe, 1987) used in figure-ground segregation (see Humphreys & Price, 1994; Humphreys, Riddoch, Quinlan, Price, & Donnelly, 1992). From this perspective, simultanagnosia may represent a mild form of "apperceptive agnosia". As pointed out by Humphreys and Price (1994), patients with a deficit in discriminating shape features would (1) fail to engage attention ef-

ficiently on objects; (2) show poor figure-ground segmentation; (3) show inappropriate grouping of features that are similar but belong to different objects (which would, in turn, impair the recognition of complex visual stimuli); and (4) fail to recognise objects seen in impoverished conditions (e.g. when presented only briefly).

In the present study we provide an account of simultanagnosia in the context of a single clinical case, patient AMA. Our account rests on a deficit in the early processing of visual information. Given that there are so many extant theories of simultanagnosia, and none of them can be ruled out definitively for all possible cases, why do we need another account? Our view is that the clinical typologies are greatly impoverished, and in fact often serve to blur important distinctions. The present goal is to use contemporary empirical methodologies and cognitive theory to demonstrate that at least one additional source of simultanagnosia should be distinguished. Developing a powerful taxonomy is important not only to help us understand the functions of the brain, but also as a practical guide for effective rehabilitation programmes; depending on precisely what is awry, different techniques for teaching compensatory strategies will be more or less appropriate.

## Spatial Indexing Deficits

Several researchers (e.g. Julesz, 1984; Neisser, 1967; Treisman, 1977) have identified a pre-attentive stage of processing, during which perceptual features are extracted in parallel across the visual field. These basic features, once extracted, can be *indexed*. Indexing makes locations explicit in a way that allows them to serve as anchor points for additional visual routines (Ullman, 1984). Visual routines are sequences of operations that define properties of, and spatial relations among, objects. According to the theory, as part of the process of indexing, pre-attentive parallel processes identify "odd-man-out" features. The greater the difference between a feature and those surrounding it, the more easily it can be indexed. One characteristic of such elementary features is that they immediately seem to "pop-out" from the background (Treisman,

1977). Parallel selection without focal attention can occur for many classes of visual cues (e.g. Donnelly, Humphreys, & Riddoch, 1991; Duncan & Humphreys, 1989; Enns & Rensinck, 1992; Treisman, 1977; Treisman & Gelade, 1980; Wang, Cavanagh & Green, 1994; Wolfe, 1992b; Wolfe, Cave, & Franzel, 1989). Wolfe and Bennett (1996) have suggested that preattentive processes can "carve" the visual input into proto-objects.

According to Ullman's theory, another function of visual routines is to shift the "spotlight of attention", to bring into the processing focus specific features (or clusters of features, textures). This requires, according to Ullman, a *spatial indexing* stage. The locations and areas of the selected features are made explicit and used as prospective targets (anchor points) for a directable "spotlight" that travels at much higher speed than an eye movement. In Kröse and Julesz's (1989) conception, pre-attentive selection of items and their spatial indexing can be described as performing "roughing and zooming" operations. The "attention window" is shifted and adjusted to envelope the area of the prospective form. The goal of indexing is to provide anchor points that help bring focal attention to items, which in turn channels visual information to specialised systems for shape and space analysis in parts of the system that are further downstream.

How can these ideas about spatial indexing help us to understand simultanagnosia better? Consider a visual system in which any of these mechanisms are damaged, and consider how the rest of the system would (or would try to) cope with such loss. If attention is required to perceive a stimulus in the visual field, and if the low-level cues that draw attention (e.g. feature gradients) are no longer effective, several visual problems would follow. First, one would either inspect a display randomly or via top-down strategies. Especially for displays in which the spatial distribution of stimuli is not known in advance, visual inspection should be dramatically slowed down. Moreover, if one must see the relations among multiple stimuli in order to identify a display, a problem in shifting attention to indexed positions would produce classic symptoms of simultanagnosia. Specifically, the patient should have difficulty in quickly grasping the meaning or

theme of complex scenes (because this would seem to require rapid switching of attention and eye fixations to its various elements), in disentangling the elements contained in overlapping line-drawings (if the shifting and enveloping of an attention window to each of the separate contours is necessary to identify them), in counting the number of static elements in a display (because low-level cues would not invoke an orderly visual search of the items), in naming brief displays of multiple figures (because of the difficulty in automatically directing attentional to each location of the individual figures), and even in searching for a simple target feature (because search would be reduced to a random walk over the display or be entirely under volitional control, for instance a serial left-to-right and top-to-bottom search). Moreover, if the control of eye fixations does not benefit from low-level cues, an everyday cognitive task such as reading should also be impaired (because each printed word would be difficult to segregate as a separate visual unit).

We administered a set of tasks to one simultanagnosic patient in order to discover which of the above accounts could illuminate the nature of her problem; if we looked carefully, could we discover deficits of that would follow from disruptions of specific mechanisms but would not otherwise be expected?

## CASE REPORT

AMA is a 31-year-old woman who had a motor vehicle accident in February 1995. She suffered head trauma with loss of consciousness, and received emergency care for about 24 hours after the accident. Contusions were observed over the left parietal and the left frontal regions of the head. A cranial CT at that time documented a fracture, which extended across the left parietal bone through the mastoid and across the external auditory canal. She had a contusion with blood in the inferior left temporal lobe and a contra-coup injury in the right lateral inferior surface of the temporal lobe, with cerebral contusion/haematoma, and also a contusion in the inferior frontal operculum on the right. She was treated with Dilantin for seizure

prophylaxis. She had no seizures or evidence of CSF leak. Her past medical history was unremarkable.

We met AMA about 1 month after her accident. At this time, and thereafter, she did not show any obvious abnormalities on informal inspection nor in casual conversation. At our initial neurological examination, she appeared fully oriented and alert. Her speech was fluent, coherent, and she could engage on a wide range of topics and had retained a quick sense of humour. Her memory seemed intact (see later sections for more detailed information). AMA's neurological deficits included a loss of hearing on the left, and difficulty with balance and walking. There was horizontal nystagmus on left lateral gaze. She also had a sense of clockwise rotational vertigo induced by sudden head movement. Both the nystagmus and vertigo were considered to be a manifestation of left vestibular damage caused

by the parieto-temporal skull fracture. Her principal complaint regarding her mental functions was a marked difficulty in reading. AMA is an Ivy League graduate in English and Economics, and therefore is more highly educated than the average American of the same age. Indeed, prior to her accident, she used to be an avid reader. In traveling from her home in Boston to the cognitive neuroscience laboratory in William James Hall (at Harvard University), she independently used public transportation and was never late or missed any of her appointments. She seemed to have remarkable insight into her problems, and enthusiasm and curiosity about our research.

Neuropsychological testing of memory and perceptual functions showed no deficit in: memory for verbal material while recollecting unrelated sentences or short stories<sup>1</sup>, short-term spatial memory<sup>2</sup>, shape discrimination and memory<sup>3</sup>, or in

---

<sup>1</sup> AMA was able to repeat with no errors unrelated sentences (Ostreicher, 1973) that ranged from 4 to 12 syllables in length. For sentences of 16–24 syllables, she made only 2 errors. Only for the longest sentences (28 and 32 syllables) did she leave out the embedded clauses (10 syllables on average). Her performance was within the normal, lower, range. Her recollection of two stories (i.e. "The lion called Sultan" by Barbizet & Cany, 1968: and "The cowboy from Arizona," see Talland, 1965; both discussed in Lezak, 1976) was better than normal (both at immediate recollection and 1 hour later).

<sup>2</sup> AMA remembered without error, after a 5-minute delay with a verbal filler-task, where the experimenter had hidden from sight three small objects (keys, an eraser, a coin). In the Corsi blocks spatial memory test (Lezak, 1976), AMA could easily tap the first three spatial positions in any sequence, but she would lose track of the following blocks, although for the fourth block position she could correctly select a spatial neighbourhood of two or three alternative blocks. She was always aware of how many blocks she missed; she had no trouble counting how many blocks had been tapped at each sequence. On the basis of our hypothesis, we would have expected a greater impairment than the one shown here. However, it is possible that AMA could be using the strategy of remembering a short sequence of eye fixations while following the finger movements.

<sup>3</sup> We examined AMA's ability to discriminate between different shapes. In the first task, AMA was given 10 trials from the Visual Pattern-matching task (Newcombe, 1969). In this task, meaningless black-and-white line drawings and patterns are shown on the left side of the page and have to be matched to an identical version on a row of three other highly similar shapes. AMA performed this task effortlessly and flawlessly. She also performed 10 trials from the Hidden Figures test (Talland, 1965), where she was requested to identify and mark a simple geometrical shape that was embedded within a more complex meaningless shape. Again, AMA committed no errors in this task. Since the above matching tests did not require her to hold a visual shape in short-term memory, we devised another computerised test with a new set of figures. In this task, a figure appeared at the centre of the screen within a 12.5 x 7.5cm frame for 3sec, and after a blank screen of 4sec, it reappeared either above or below an identical frame containing a different figure. The subjects' task was to select the matching drawing by pressing one of two keys, one above the other, labeled B or T (for bottom and top drawings). This task included a total of 20 trials. Initially we used drawings of animals, but later used meaningless figures after it became clear that she memorised the animals' names. The stimuli were black-and-white line drawings taken from the Kimura Recurring Figures test, a memory test designed to minimise a verbal strategy. AMA accurately discriminated the meaningless shapes (she committed only one error, and so did one of the four controls). However, her average response time (recorded from the onset of the second screen) was significantly slower than that of three controls [AMA: Mean = 2815, SD = 1772; Controls: Mean = 794, SD = 419,  $t(38) = 4.9$ ;  $P < .0001$ ].

drawing<sup>4</sup>. Also, AMA showed no signs of visual spatial neglect<sup>5</sup>. However, whereas her simple response time (RT) was normal (see Fig. 1), she was clearly slow when required to make a choice between two responses, regardless of whether the responses were made to visual or auditory stimuli<sup>6</sup>.

## BRAIN IMAGING

Standard clinical magnetic resonance imaging sequences were obtained at the Massachusetts General Hospital's MRI imaging centre in March 1995. A (3D) MRI sequence was conducted in February

1996. Both sets of scans demonstrated focal areas of contusion of the cerebral surface. These were distributed to the anterior lateral and ventral temporal lobes, bilaterally, and were associated with small haemorrhages. There was also evidence of a more general cerebral injury, which was more prominent on the right than left.

Three focal lesions were centred on the surface of the right cerebral hemisphere (RH). As illustrated in Fig. 2, the largest lesion in the RH was centred in the superior temporal gyrus, just at the most rostral level of the lateral projection of Heschl's gyrus. The crown of the superior temporal gyrus was splayed open with rupture of the full

<sup>4</sup> We presented AMA with simple line drawings of a flower and of a house. Her copies of both drawings were clearly recognisable and detailed, and they were apparently done without much effort. The same could be said for the drawings from memory of the same house and of a generic clock face and a bicycle. No elements of the house were omitted and the copy and memory test appeared almost identical, even though there was a delay of several seconds between them—and she was not forewarned of the memory test. The digits of the clock face were all in the correct locations and drawn in neat Roman numerals. All the essential parts of the bicycle were drawn in their correct spatial relationships. A copy of the Osterrieth-Rey figure was flawless, and the rendition from memory was better than normal average (her score equaled 34 points on Taylors', 1959, scoring system).

<sup>5</sup> AMA performed a paper-and-pencil cancellation task (designed by Weintraub & Mesulam, 1987), which requires the patient to identify multiple instances ( $N = 60$ ; 15 in each quadrant) of a wheel-like shape within a large array of foil shapes ( $N = 360$  on a  $34 \times 28$  cm sheet) that vary in similarity to the target. AMA marked all the targets, and her search appeared systematic (left-to-right, top-to-bottom search). In addition, AMA performed a line-bisection task. In this classic neurological task, subjects (AMA and five controls) were asked to mark the centre of a black horizontal lines (23 cm long and 4 mm wide), which were presented 10 times (in series) at the centre of separate white sheets of paper. The deviations from the actual centre were converted to signed (positive if bisections were to the right, negative if to the left) percentage error scores. Although AMA's deviation scores did not qualify for unilateral neglect (mean error = 3% of line length), the variance of her deviations was larger than that of the controls (AMA = 8.6; control 1 = 0.94; control 2 = 1.3; control 3 = 1.5; control 4 = 2.2; control 5 = 2.5). Interestingly, AMA reported that when looking at one end of the line she would "lose" the other end (cf. Luria, 1959).

<sup>6</sup> A simple reaction time paradigm was used to determine whether AMA may have had developed as a consequence of her head trauma a generic problem in motoric speed. It is in fact a common consequence of traumatic brain injury (which often involves diffuse damage) that the speed of RTs is slowed (see van Zomeran, 1981). In one task a fixation point (a small cross) appeared at the centre of the screen. The subjects were instructed to fixate on this point, and then press the space bar while maintaining fixation. A black five-pointed star (2 cm in size from two opposing vertices) appeared at the position of the fixation point 1, 1.5, 2, or 2.5 sec after the subject pressed the space bar. The subject was to press the space bar again, as quickly as possible, as soon as the target appeared. There was a total of 20 trials (5 trials for each delay). The different delays were ordered randomly. Five control subjects were tested. An ANOVA with group (AMA vs. Controls) as the fixed factor and delays (1, 1.5, 2, or 2.5 sec) as the within subjects factor showed no reliable difference [ $F(1,4) = 3.2$ ;  $P < .015$ ] between AMA (mean = 277 sec; SD = 46) and the controls (mean = 368 sec; SD = 69) or the interaction of group with delays [ $F(3,12) = 1.1$ ;  $P < .40$ ]. Instead, RTs decreased for all subjects with increasing delays between the first key press and the stimulus onset;  $F(3,12) = 4.5$ ;  $P < .04$ . It is clear that generalised motoric slowing cannot account for AMA's relatively slow responses. An alternative account is that AMA has difficulty when one of two (or more) different responses need to be selected. Alternatively, AMA may be slow only when she has to select a response associated with a specific stimulus (i.e. following a visual discrimination task); this difficulty could be general, or could occur only for visual stimuli. We tried to discriminate among these alternatives with two choice-RTs tasks: in one, a target (either the same star used in the previous task and one coin from Experiment 3) had to be recognised, and the key corresponding to that shape had to be pressed; in another, the computer spoke the name of one of the two stimuli (i.e. on hearing "star" or "coin"), and the subject pressed the corresponding key. There was a total of 20 trials (10 for each stimulus in random order) in each task. As is evident in Fig. 1, in clear contrast to the previous task where only one simple response was required, AMA required more time to respond than the controls in both of the visual task [ $F(1,4) = 10.2$ ;  $P < .03$ ], and the auditory task [ $F(1,4) = 17.5$ ;  $P < .01$ ]. Clearly, AMA is slow when she must choose between more than one type of response, and this is true in both visual and auditory modalities.

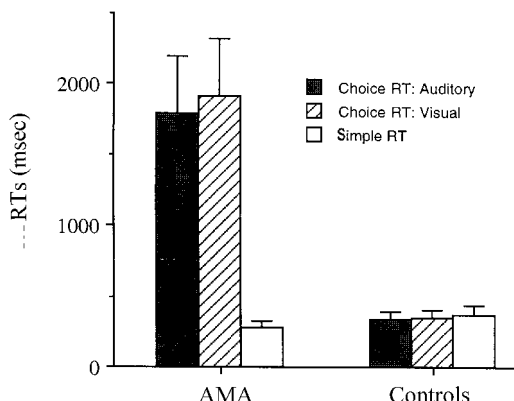


**Fig. 1.** Simple and choice RTs (auditory and visual): Means and SD.

width of the cortex. A haematoma, lying within the white matter subjacent to Heschl's gyrus, extended caudally to the anterior region of the planum temporale (Fig. 2, panel D). The total extent of this lesion involved the zone of convergence of T1a/T1P, PT, and HI. A secondary lesion in the RH (Fig. 2, panels B-E) lay associated with effacement of the crowns of the medial and inferior temporal gyri; this lesion began caudally near the caudal end of T2p and T3p, where it was most severe, and extended to the more rostral regions of T2p, T3p, and throughout the full length of T2a, T3a, and fully through the extension of the middle and inferior temporal gyri to the temporal pole. A portion of the cortex of T3p in the inferior temporal gyrus was completely effaced. The inferior temporal fissure was splayed open with about 50% of the abutting white matter destroyed. The central white matter of the temporal lobe was reduced in volume from the level of the surface lesions all the way to temporal pole. Finally, a third lesion was located in the inferior frontal gyrus of the RH (Fig. 2, panel F). As illustrated in Fig. 3 (right panels), the cortex appeared to be ruptured open, and there was a small haematoma that extended from the plane of the cortex into the immediately subjacent white matter.

As evident in Fig. 2, a single lesion in the left cerebral hemisphere (LH) involved effacement of crowns of the inferior temporal and fusiform gyri; this lesion began caudally within two planes of the caudal end of TO3, and extended through the more

rostral region of T3p and the caudal half T3a. It also extended medially through the caudal third of TFa. There was also a small (about 1cm in anterior-posterior extent) haematoma in the superior parietal lobule (see Fig. 3, left panels), including a bit of the supramarginal and postcentral gyri with a slight effacement of the cortex of both gyri.

The lateral ventricular system was enlarged moderately throughout, and there was a subtle patchy pattern of signal intensity inhomogeneity throughout the entire cerebral white matter, evident particularly in external sagittal stratum, coronal radiata, and the corpus callosum. There was no explicit focal injury in these fibre systems nor, in particular, in the superior longitudinal fasciculus.

## GENERAL METHODS AND PROCEDURES OF THE EXPERIMENTS

All of our testing involved visual material, typically presented on a computer screen. The patient was familiar with computers and used to typing, and she found it natural to work on our Macintosh II. During these tasks she would sit at a comfortable distance from the display (approximately 50cm from the screen, without a chin-rest) and would use either the right hand or both hands for responding (when the task required key presses). AMA's vision was corrected to normal by contact lenses or glasses. All computerised tasks were administered by means of MacLab software (Costin, 1988). Most stimuli were drawings digitised by a Microtek Scanmaker 600ZS and editor using commercial software (e.g. Adobe Photoshop). The testing took place in several sessions, 3 to 7 months after the accident. Although our discussions of the experimental results do not follow the exact chronology of testing, repeated tests of AMA's reading skills confirmed that her impairment was stable during the entire testing period. Control subjects were tested in those tasks where the performance of appropriate control subjects was not already known. These control subjects were all volunteer females matched to AMA for year of birth ( $\pm 2$  years) and years of education (they all had at least a college degree). Because of the limited availability of these control subjects, these

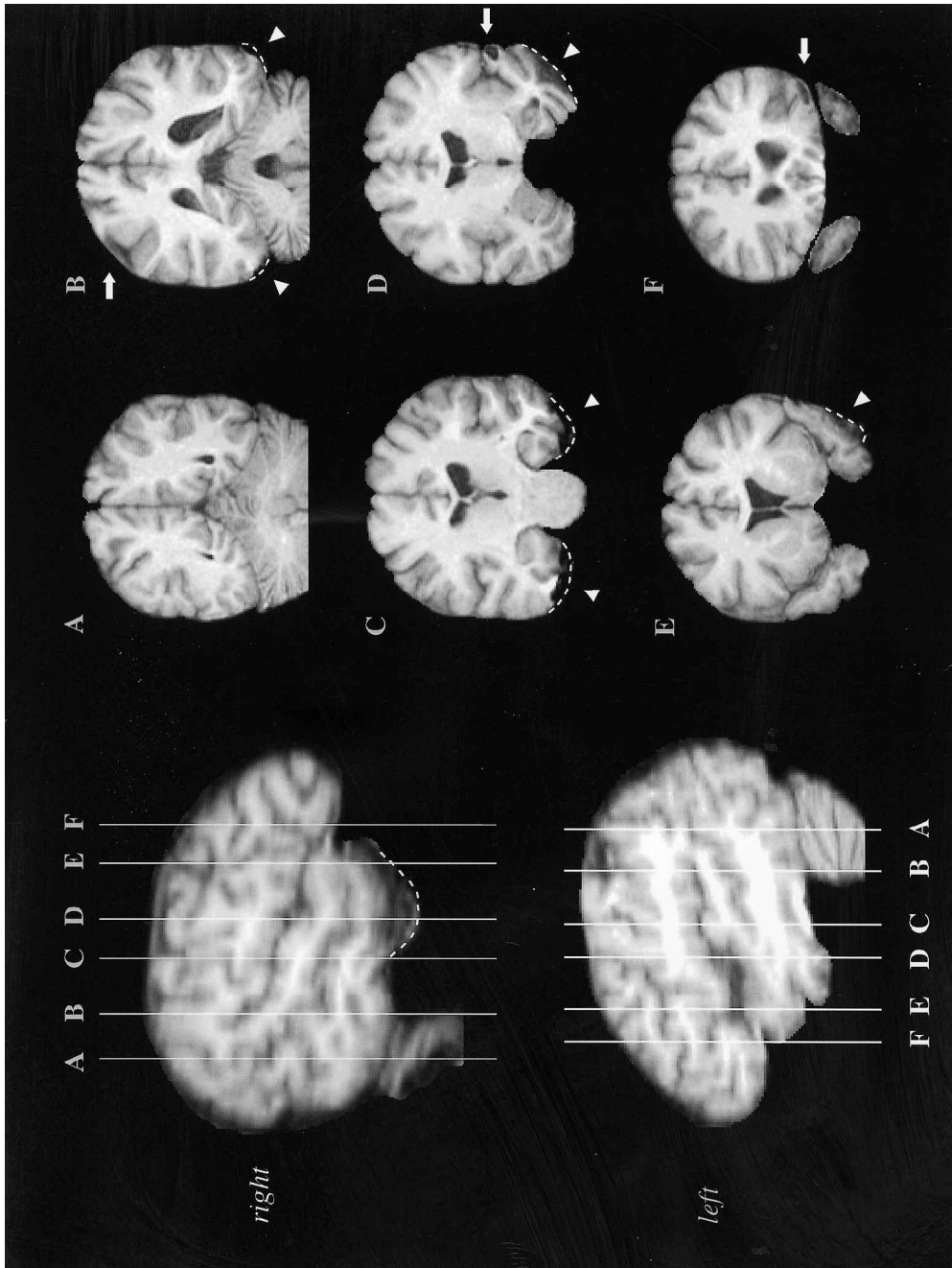


**Fig. 2.** Brain imaging (left side of coronal images always corresponds to the left side of the brain). Parasagittal views of the left and right hemispheres, transected by vertical lines at anterior-posterior levels for the corresponding coronal slices (panels A-F). Small white triangles are used to point out the primary lesion of the temporal cortex. Arrows (also white) indicate the presence of haematomata in the supramarginal gyrus of the left parietal lobe (panel B), the superior temporal gyrus of the right hemisphere (panel D) and the right inferior frontal cortex (panel F).

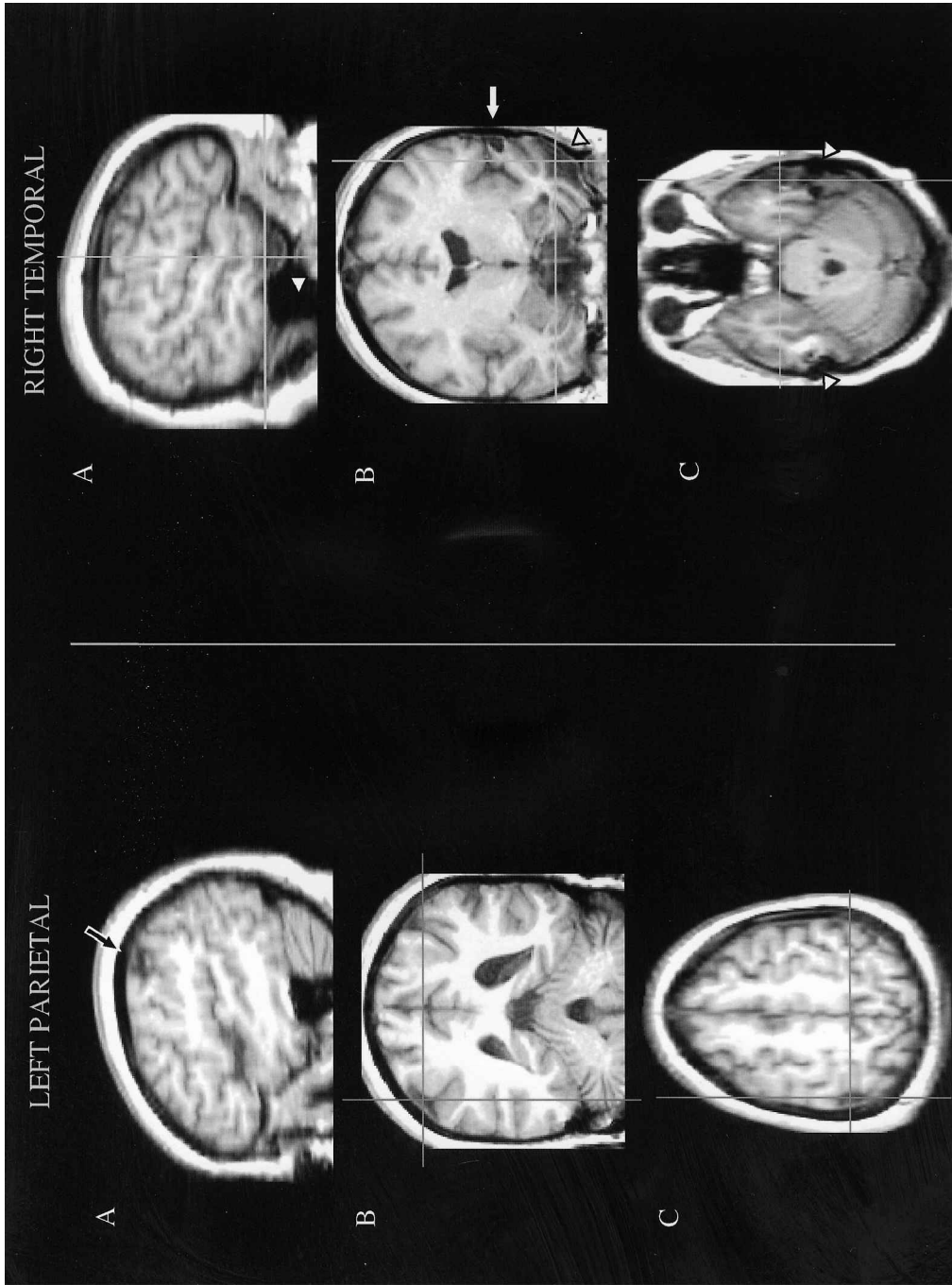


**Fig. 3.** Brain imaging (left side of coronal and horizontal images always corresponded to the left side of the brain). Cross-sectional view of the haematoma in the left parietal lobe and lesions in the right temporal lobe. Projection lines indicate corresponding levels of intersecting planes which come together to the same location in the brain. Small white triangles are used to point out the primary lesion of the temporal cortex. Arrows (black in the left hemisphere, white in the right) indicate the presence of haematomata.

subjects were often not the same individuals from task to task and the exact number used for each task is specified in the tasks' experimental procedures.

In addition, outliers among the RTs were trimmed prior to analysis of each task; outliers were defined as RTs greater than 2.5 SDs from a subject's mean RT in a particular cell (combination of levels on the independent variables). In each Results section, the percentage of discarded trials is noted only if there were any outliers for that task.

## PART 1: ESTABLISHING THE PRESENCE OF SIMULTANAGNOSIA

In this section we present results from classical clinical tasks in order to establish that AMA has the key symptoms of simultanagnosia.

### Experiment 1: Description of a Complex Scene

As an initial effort to use clinical tasks to document that AMA could be diagnosed as having simultanagnosia, she was shown "the Telegraph Boy" picture from the Binet scale. Normal adults can describe this picture at a glance as that of a mail-delivery boy whose bike's front wheel has come off and who is waving, presumably for help, to an oncoming car.

**Methods.** A 22 x 25cm copy of the picture was shown to AMA with the instruction to "tell me what the picture is about". The investigator took a rough measure on his watch of the duration of AMA's comments

**Results.** AMA required about 1 minute to arrive at the correct interpretation of the drawing, and her description revealed a clearly piecemeal approach to comprehending the scene. The first element she mentioned was a man and, after several seconds, the car. After another pause, she noticed that the man was lifting an arm and holding a cap, and only then seemed to see the bike and concluded that the man had been on the bike. After a pause she mentioned the telegram. She then added that the man on the bike must be waving to the car. Only at this point did she notice that the wheel was off the bike and

inferred from this that he was asking for help. Classic cases of a simultanagnosia (e.g. see Williams, 1970) exhibit a very similar approach when describing this same drawing.

### Experiment 2: Perception of Overlapping Figures

Inability to identify overlapping figures is a classic sign of simultanagnosia; thus, we tested AMA on this task.

**Methods.** Two line drawings (from Luria's, 1966, modification of Poppelreuter's figures) that contained sets of overlapping common objects were shown to AMA. Drawing 1, shown in Fig. 4, included five overlapping pictures of objects that appear on dining tables (a teapot, a bottle, a fork, a glass, and a bowl). Drawing 2 included overlapping drawings of four types of headgear (i.e. a crown, baseball cap, top hat, and fedora). AMA was simply asked to describe what was present in the drawing.

**Results.** In examining Drawing 1, AMA appeared puzzled and identified only the teapot after approximately 10sec. When questioned about the possibility of seeing something in the drawing other than the teapot, she claimed she could only see "a bunch of meaningless lines". Then, after a long inspection of several more seconds she saw the fork (with surprise), and reported that initially it appeared to her as something dripping from the side of the teapot. Asked about a possible meaning of the other lines she asserted that she had no idea. Only after the investigator pointed to the bottle in the drawing

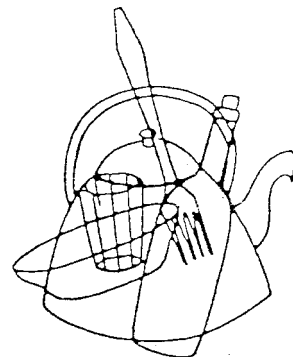


Fig. 4. Overlapping figures (Drawing 1).

did she recognise it, and added that she had initially seen the cork as part of the teapot. In looking at Drawing 2 (although at this point she should have been forewarned by the previous drawing about the nature of the task), she reported seeing only a baseball cap. After several seconds of inspection, she identified something like a "theatre light". She identified it correctly as a top hat (and immediately thereafter mentioned the fedora) only after the investigator asked her to find the crown. Her responses were clearly similar to those of classic simultanagnosic patients.

### Experiment 3: Counting a Set of Objects

In its classical administration, the following task requires the subject to view a row of coins and to count them. In our version of this task, American pennies were digitised and the images were edited to create displays of different numbers of coins (from 2 to 7). There were two tasks. In the first task ("limited time"), the coins remained visible for 1sec. If AMA has trouble "grasping" multiple stimuli, the time constraint should affect her accuracy considerably. In a second task ("unlimited time"), we explored AMA's performance (and that of the same controls) when there were no time constraints. We would expect AMA's performance to be more accurate in this task than in the previous one, although her abnormal performance should be clearly reflected in the time she required to respond.

#### Task 1: Limited Time

*Methods.* The coins appeared on the screen at their actual sizes and appeared in random positions (different on every trial) for 1sec. There were 4 trials for each of the 6 set sizes, for a total of 24 trials in the task. The subject pressed the space bar to initiate a presentation, and then pressed the key that corresponded to the number of coins. Eight matched control subjects performed the task.

*Results.* In those trials in which four to seven coins appeared, AMA reported seeing only three coins 70% of the time. She reported seeing four coins on only one trial (when there were seven), and during the course of the entire test she was correct on only two trials on which there were two or three coins.

Thus, within the limited time of 1sec, AMA could detect only a small set of visual items. It may be of interest that when she reported fewer coins than were actually present, she claimed to have the "feeling" that there were more coins than she could actually count. AMA was also asked at the end of each trial to guess the range of coins that may have been on the screen and that she may have failed to see clearly. She reported that there may have been from 4 to 10 on average (and for a trial with 7 coins, she gave a possible range of 4 to 15). In contrast to AMA, the controls performed with high accuracy at the counting task (five of the eight control subjects performed perfectly and three committed just a single error, of only a one-coin difference).

#### Task 2: Unlimited Time

*Methods.* The stimuli were identical to those in the previous task, but they now remained on the screen until a key press was made. RTs were collected and, in order to have a better estimate of both accuracy and speed, we doubled the number of trials ( $N = 48$ ).

*Results.* In this version of the task, the control subjects performed perfectly and responded more quickly than AMA (with mean RTs of 1495 msec,  $SD = 624$ , versus 7731msec,  $SD = 5806$ , respectively). AMA still committed errors in 20% of the trials (in counting 7 and 6 coins).

Given that AMA and the control subjects differed greatly in the variance of their RTs, we performed two separate analyses of variance on the RTs with replications as the random effect (the controls' RTs on each trial were averaged in order to have the same number of replications as in AMA's analysis) and number of targets (two–seven coins) as the fixed effect. The analysis of the controls' RTs showed that their performance differed for different numbers of targets;  $F(5,14) = 12.86$ ;  $P < .0001$ . As Fig. 5 shows, the control subjects counted two, three, or four coins in about the same amount of time, whereas they required more time for larger numbers of coins. This finding replicates the subitising range effect (e.g. Mandler & Shebo, 1982). Post hoc Scheffé's  $t$ -tests confirmed that RTs for two versus three or four coins did not differ,

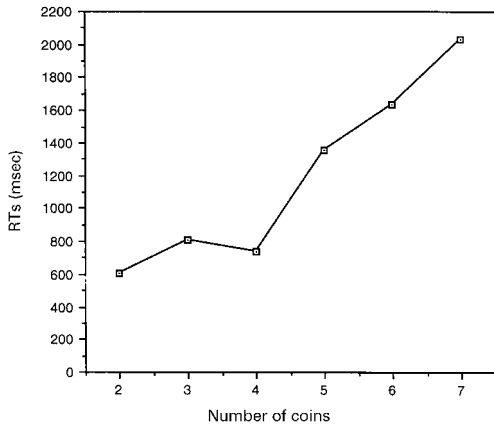


Fig. 5. Counting coins: Controls' mean RTs.

whereas RTs for all of these amounts of targets differed from those in the five, six and seven targets conditions ( $.001 < P < .05$ ). Moreover, because there was an abnormally large variance in AMA's RTs, we analysed her results using a nonparametric test, the Kruskal-Wallis one-way analysis of variance (Howell, 1987). This test confirmed an effect of the number of targets on the time AMA required to count,  $H(5) = 58$ ,  $P < .0001$ . However, as is evident in Fig. 6, there was no subitising range advantage, as confirmed by another Kruskal-Wallis test performed on only the conditions with two–four coins,  $H(2) = 32.5$ ,  $P < .0001$ .

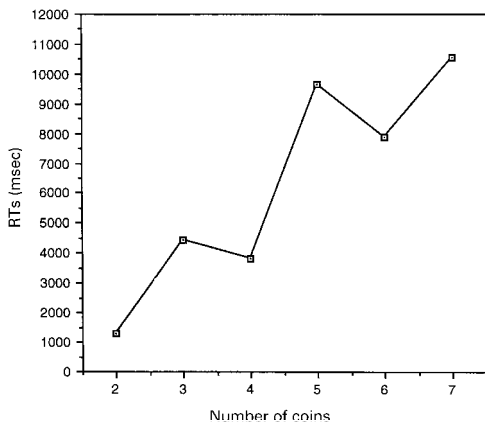


Fig. 6. Counting coins: AMA's mean RTs.

In short, like classic simultanagnosics, AMA did not perform within a normal range in this counting task, even with unlimited viewing time when six or more coins were present. Possibly, with smaller numbers of coins it was easier for her to encode the spatial coordinates of each coin, whereas with greater numbers of coins such spatial encodings may have been more easily confused. The long RTs suggest that locations may have been found through serial, perhaps random, search. Indeed, during the task, AMA commented that she did not know whether she had already counted one specific coin.

### Experiment 4: Naming of Multiple Objects

Another classic test of simultanagnosia is the ability to name multiple objects, which was assessed here.

**Methods.** In this task, drawings of common animals were shown on the computer screen for 1sec. Each drawing could occupy an area of the screen no greater than 5cm in diameter. Drawings of 3–7 animals were presented in different arrays, in random positions on the screen, for a total of 10 trials. The subject's task was to name all the animals she could recognise.

**Results.** The eight control subjects were able to report in a single trial a range of three to six animals, without committing naming errors. AMA was always correct in her naming, but was able to report only one animal on each trial. As in the coins task, she claimed that she could see at least two or three additional things, but that they appeared as "just dark lines" to her.

### Experiment 5: Assessing Reading Deficits

Characterisations of simultanagnosia sometime note that the patients have reading problems and that they tend to read a letter at a time. Thus, we wanted to assess whether AMA did in fact have such a class of deficit. Informally observing AMA while she read different texts suggested that her reading was abnormally slow and very poor. AMA could read only very short (two or three letter) words (e.g. prepositions) at a normal speed, regardless of the size of print. She spelled longer words

letter-by-letter (in left-to-right order) to infer the sounds of each syllable (typically aloud or under her breath). AMA would then put together a string of syllables until she obtained, by trial and error, the correct pronunciation of the word. Once the word was read, she had no doubt about its meaning. Single letters (even when rotated) were read with no errors or apparent effort, and she could easily distinguish between normal and mirror-imaged letters.

In contrast to her dyslexia, AMA did not exhibit any agraphia or dysgraphia. She could write words or long sentences (e.g. 10 words) in a very clear handwriting and without hesitation or errors regardless of how long or infrequent the words (e.g. "neuropsychology"). Consistent with her difficulty in reading novel material, when later presented with her own writing she was unable to read it any better than printed text.

*Methods.* Ten high-frequency and 10 low-frequency words (according to Kuçera & Francis, 1967), ranging from 3 to 10 letters in length (18 point, bold Geneva font), were presented for 500msec or 1sec centred on the computer screen.

*Results.* When the words were presented for only 500msec, AMA reported, on average, only two letters ( $SD = .08$ ) of each word, at either the beginning (70%) or the middle (25%) of the words. She read correctly the word "dog" and guessed "automobile" from the letters "au-t". When the words were presented for 1sec, her average letter span was 3.6 letters ( $SD = .07$ ), which allowed her often to read correctly four-letter words (e.g. "hand") and to make good guesses about longer words (e.g. "mani-" = "manicure"). The control subjects made no errors.

## Discussion of Experiments 1–5

AMA's performance in these experiments supports the diagnosis of simultanagnosia. Her performance in these tasks was highly reminiscent of the performance of other cases described in the literature. Moreover, her introspections are also consistent with this diagnosis; she defines her problem as "not being able to follow more than one thing at the

time", and also describes her visual experience as like "a video-clip" (e.g. an MTV programme), where scenes follow each other quickly, without smooth transition or a sense of continuity.

The different accounts of simultanagnosia that we sketched in the Introduction would predict most, if not all, of the failures in the classic simultanagnosia tests just described. Specifically, a problem with the size of the attention window would make it difficult to appreciate a complex figure and disentangle overlapping drawings, and searching for items in a set of objects in order to count or name them may become a slow and cumbersome task. Similarly, double-disengagement difficulties would cause problems with inspecting any stimulus other than the one that happens to be under focus. This account easily allows us to understand AMA's performance when describing a complex thematic figure or overlapping line-drawings, counting a set of objects, and naming multiple objects seen at brief exposures. Slowed visual attention would seem to account adequately for the slowed comprehension of the complex figure and the defective grasping of several simultaneous objects seen at brief exposures. It is unclear, however, how this account would explain such a remarkable problem with overlapping figures. A deficient spatial mapping may cause the patient to lock onto (perceptually) a single form to the detriment of others, thus causing problem with all the four tasks. Analogously, deficient pattern analysis (i.e. in feature extraction and parsing) would make a form difficult to distinguish from other forms, thus causing problems in interpreting complex and overlapping figures and also reducing the efficiency with which the visual system could detect and identify any specific item in a set.

It is of particular interest to us to evaluate whether AMA's performance in these tasks can also be accounted in terms of the spatial indexing model.

1. Complex figures should be difficult to interpret if significant elements of the scene cannot be indexed. In particular, there should be difficulty in integrating various objects that form a thematic figure, because the deficit could cause slow and imper-

fect recovery of spatial relations among the objects (cf. Ullman, 1984). If inspection time is unlimited, we expect spatial relations to be recovered eventually by use of random ("reaching in the dark") operations.

2. *Prima facie*, an impairment with the overlapping figures test would not seem to imply a problem with spatial indexing. In this test, all the objects are roughly in the same spatial location; therefore, a spatial search for the objects in the drawing should not be necessary. Nevertheless, following the contour of each drawing with a pencil demonstrates that the contours are in different positions on the page; thus spatial indexing of the contours is necessary. Indeed, AMA's performance was abnormal when asked to identify overlapping line-drawings.

3. Without rapid indexing, counting a set of objects should become slow and effortful; moreover, the subitising range advantage (i.e. the limited range of items—about four items or less—than can be indexed in parallel) should disappear. We did in fact observe both of these phenomena in AMA's performance.

4. Finally, if a spatial indexing process is damaged, fewer objects should be named in briefly presented displays. In this case, the patient should be able to name only those objects that randomly fall into the focus of vision. And, indeed, AMA could name only one object at 1sec presentations.

AMA also had a clear reading deficit. Several models can account for letter-by-letter reading as a specific problem in identifying the visual form of letters and words (e.g. as a deficit in "letter activation," Behrmann & Shallice, 1995). When seen in the light of the different accounts of simultanagnosia, letter-by-letter reading appears as an emergent strategy that the patient develops to cope with one specific task, while underlying the phenomenon there may be more general visual problems. Although not all of the existing accounts of simultanagnosia have stressed the link between the syndrome and a problem in reading, some of these accounts can predict it easily. In particular, letter-by-letter reading may be expected if visual attention is severely restricted or if there is neglect or double-neglect. A problem in pattern analysis, in

particular the extraction of low-level features, could also lead patients to develop a letter-by-letter reading strategy (as exemplified by case HR of Rapp & Caramazza, 1991). In addition, an impairment in spatial indexing could produce an impairment in reading. Spatial indexing would provide information about several properties of all classes of visual input, at either a global or local level. For example, parsing (e.g. grouping of letter strings by proximity) may determine both the end-points of a word and the spacing between words (cf. Inhoff, 1989; McConkie & Zola, 1986; Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner & Pollatsek, 1981). Indeed, a location-indexed representation would seem to be required in order to proceed successfully along one line of text, move from the end of one line to the beginning of the next, and return to previously read words (see McConkie & Zola, 1986). Damage either to parsing or to a location-indexing mechanism could cause difficulty in moving the attention window to each word or it could make the word boundaries difficult to index. Similarly, we would expect difficulty in adjusting the scope of attention to encompass an entire string of letters, if a long word, one chunk of it (cf. LaBerge, 1983; LaBerge & Samuels, 1974; O'Regan, 1981, 1984). Thus, serial (letter-by-letter) reading can be seen as a compensatory procedure in the absence of an indexing mechanism. This compensation would consist of the narrowing of the attentional focus to the angle subtended by one item, and the use of a voluntary and systematic serial scanning to determine the locations of the letters.

## PART 2: EVIDENCE THAT AMA HAS A SPATIAL INDEXING DEFICIT

All the previously observed "simultanagnosic" symptoms may well be due to a problem with attention window shifts and adjustments, spatial indexing or mapping, pattern analysis, or a combination of damage to any of these mechanisms. In the following experiments we attempted to narrow down the range of alternatives and provide evidence supporting the presence of a spatial indexing deficit.

## Experiment 6: Visual search for One Target Among a Variable Number of Distractors

Treisman and her collaborators (e.g. Treisman & Gelade, 1980; Treisman & Gormican, 1988) have demonstrated a “pop-out” effect in which an item that differs from the others in an array by a simple, salient feature is detected automatically (i.e. without focal attention; see also Sagi & Julesz, 1985a,b). Such detection is equally fast when different numbers of distractors appear with the differing item. Treisman and her collaborators hypothesise that the target is identified pre-attentively (i.e. in parallel across the whole field of vision), and its presence draws attention to it; in our terms, the item is immediately indexed and the attention window can rapidly shift to its location.

In addition, Treisman and her colleagues suggest that in order to identify the detected feature (e.g. whether an odd item is oriented differently from the other items), one must serially shift focal attention to the item; in fact, when subjects are required to identify multiple items, they typically require more time when larger numbers of items are present. This result suggests that items are examined one-by-one by a serial attentional process. Duncan and Humphreys (1989) proposed that, after the parallel segmentation of a display of a target among distractors, the input “descriptions” are matched against a “template” of the target by immediately orienting attention to the segmented input; thus, the input can be matched to the template equally easily with different numbers of distractors. In contrast, Wolfe, Cave, and Franzel (1989) have suggested that searches for basic features and for feature conjunctions do not differ qualitatively but only quantitatively. According to this view, parallel processes provide signals to guide the attentional focus to the target; unique simple features simply generate strong signals (or, we suggest, could provide salient anchor points for indexing). For present purposes, the important point is that focal attention seems to be required in order to identify targets embedded in similar distractors, but not to detect such targets (Sagi & Julesz, 1985a, b).

It follows from some of the classic accounts of simultanagnosia, as well as the spatial indexing def-

icit hypothesis, that such patients should differ from normal subjects in their ability to identify odd-man-out items. Whereas normal people should require the same amount of time to identify a salient “odd man out” for different numbers of distractors, AMA should require more time when more distractors are present. Specifically, either a deficit in feature analysis or spatial indexing lead us to expect her to require serial search. If features are degraded, the “odd” items should not “pop out”. Or, if the mechanism that indexes the items is damaged, it may not selectively “call” attention to the targets. In contrast, the double-disengagement, restricted attention window, and slowness of attentional shifts accounts lead us to expect a general slowing of performance, but they do not imply that the normal parallel search function should change into a serial search with increasing number of distractors. Specifically, the double-disengagement hypothesis would predict “sticky fixation” but, once attention has disengaged, one should be able to search immediately for the target location regardless of the number of distractors. Similarly, if the attention window is so narrow that the patient can only see one item initially, because the target is examined first in a pop-out display, the number of distractors should not affect performance. Finally, if the mechanics of the attentional shifts have been impaired so that attention can move to a target but at a reduced speed, then once again we would not expect this impairment to worsen with the number of distractors in the display. Thus, the following task may allow us to begin to rule out and narrow down which cognitive mechanisms are impaired in AMA.

*Methods.* In the display, the target was a black five-pointed star (1.5cm in diameter) and the distractors were a field of coins (American pennies seen at their normal size on the screen). Both the target and the distractors appeared at unexpected locations from trial to trial. The star and coins differed clearly by at least two simple features: not only were the stars made of straight lines and the coins of curved lines, but also the star was black and the coins were gray-tone digital images of real pennies. Therefore, we expected such a display to induce

parallel search for the target in normal subjects. One, 3, 6, or 12 coins were used as distractors. For each number of distractors there were 12 trials (therefore, a total 48 trials for the whole experiment). Trials were inter-mixed randomly. The subjects, AMA and four control subjects, were instructed to press one of two keys, marked Y or N, to indicate whether they saw a black star. The display appeared as soon as the subject pressed the space bar, and it remained in view until the subject responded.

**Results.** As illustrated in Fig. 7, the control subjects required comparable amounts of time for the different sized arrays. An analysis of variance was first performed on the control subjects' data, with array size (with 1, 3, 6, or 12 distractors) and target presence (yes/no) as the within-subject factors and mean RT as the dependent variable. Given the standard results in the literature, we did not expect an increase in RTs with increasing numbers of distractors, and in fact there were no reliable differences for different the array sizes [ $F(3) = 1.6$ ] for the presence/absence of target [ $F(3) = 2.6$ ], or for their interaction [ $F(3) = 2.7$ ].

In contrast, an analysis of variance with array size (1, 3, 6, or 12 distractors) and target presence (yes/no) as the fixed effects and replications as the random effect revealed that AMA required progressively more time when more distractors were present  $F(3,40) = 23.08$ ,  $P < .0001$ , and her RTs increased more sharply for trials with no target than for trials that included the target [ $F(3,40) = 3.5$ ,

$P < 0.2$ ]. Finally, she required more time in general when the target was absent,  $F(1,40) = 5.12$ ,  $P < .03$ ]. Scheffe's tests revealed that the effect of the number of distractors occurred because RTs with 12 distractors differed from all other conditions, and the 6 distractors condition differed reliably from the 1 distractor condition,  $.0001 < P < .01$ . Fig. 7 illustrates AMA's performance in present and absent trials and each of the control subject's performance (collapsed over present and absent trials).

**Discussion.** AMA's performance suggests that all items were examined serially until, by an iterative rejection of distractors, the target was found. This interpretation is also supported by the fact that she required more time when the target was not present than when it was present, which suggests a serial, self-terminating search. These results are inconsistent with the narrow attention window, double-disengagement difficulties or attentional slowing account. These accounts would predict an abnormally slow search, but would not predict, as seen here, a drastic change of the parallel search function's slope into a serial one, increasing with number of distractors.

The present findings are consistent with a deficient pattern analysis or feature degradation. In this case, damage could produce "noise" in the system, and the sequential allocation of attention to each item would increase the signal-to-noise ratio (cf. Rapp & Caramazza, 1991). In addition, the findings are consistent with the notion that AMA's

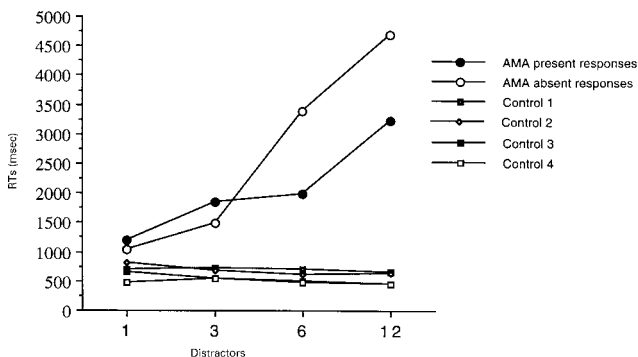


Fig. 7. Visual search: Mean RTs.

brain injury has disrupted an indexing mechanism that allows attention to shift to the location of an odd-man-out item. The indexing operation would provide information about the presence of differing visual items, which is a prerequisite to later, more detailed focal processing to obtain an explicit representation of what these items are (Sagi & Julesz, 1985a, b). If no anchor points are provided, search for a differing item will become serial and slow.

Interestingly, AMA's brain imaging results suggest that the most damage was within the ventral system. Possibly, damage to ventral areas may cause the pattern recognition system to become inefficient in its analysis of visual features, thus suppressing the odd-man-out effect. Alternatively, AMA's inability to find the target via parallel search may result from a disconnection between ventral areas responsible for parsing from dorsal areas controlling the spatial aspect of the indexing operation.

### Experiment 7: Detecting Stimuli at Changing Visual Angles

As implied by Bálint's (1995, first published 1909) or Thaïs and De Bleser's (1992) account, a patient may have difficulty perceiving multiple stimuli or complex patterns because the width of her attentional window is restricted to one object/part or it is abnormally narrow. This condition would make it difficult to attend to an entire pattern at once, or to spread attention over two or more stimuli that are not nearby. Although this difficulty by itself cannot explain the impaired performance in the previous task, it remains an empirical question whether simultanagnosia takes a specific form due to damage to several distinct mechanisms. To assess the possibility of a narrowing of the scope of attention, we tested AMA on a task that requires the subject to attend to regions that subtend different visual angles, which requires frequent changes in the size of the attentional window.

This task is of interest for an additional reason. It may help to reveal the presence of a spatial indexing problem. We have hypothesised that indexing is not simply a prerequisite for the control of movement of attention to a location but also for the adjustment of the attention window to the area of

space that the indexed form occupies. If this is the case, the spatial indexing hypothesis makes a specific prediction. In the task described next, each time the size of the stimulus changes unpredictably from one width to another there should be a cost in performance regardless of whether the change is in the direction of a narrowing or widening of the stimulus size. In contrast, the hypothesis of a narrowing of attention would predict greater difficulty with a change of the display to the large width. It is less clear what the feature analysis hypothesis would predict for this task. Possibly, it would lead us to expect greater difficulty in processing small stimuli, since the feature analysers within a small region would have to sustain a greater processing load because of the fine-grained spatial variations of the stimulus.

*Methods.* The task is part of the Harvard Visual-Spatial Battery (e.g. see Kosslyn, Brown, Riffle, & Kim, 1998), and consists of four grey squares, which form a symmetrical pattern around the centre of the field. The subjects are asked to study the squares, and then to press the space bar to initiate a trial. On each trial, one or two X marks appear on opposite squares of the pattern. The subjects are to indicate whether one or two X's fall on the squares. In half the displays, the squares are separated by 2° of visual angle, whereas in the other half of the displays the squares are separated by 7° of visual angle. If the attention window has difficulty encompassing a larger area, there should be longer RTs in the wide-spread condition. In addition, on half the trials the small-spread display is replaced by the large one, or vice versa, as soon as the space bar is pressed; on the other half of the trials, the display remains at its original size. Each type of trial occurred equally often. Thus, we can compare not only the scope of attention, but also the ability to adjust the scope of attention. We compared AMA's performance in this task to that of eight controls.

*Results.* Errors were not analysed because AMA made only 3 errors out of 72 trials. As also observed in previous tasks, AMA's RTs were slower in general (mean = 1806; SD = 549) than the controls' (mean = 680; SD = 149). For large displays, AMA's mean RT was 1826msec (SD = 484),

which is 7 SDs above that of the controls for this condition (mean RT = 695; SD = 161). For small displays, AMA's mean RT was 1791msec (SD = 466), which is 8 SDs above that of the controls for this condition (mean RT = 666; SD = 137). Thus, although AMA is clearly impaired in the task, she is not differentially more impaired with large than small displays. However, when we looked at the RTs from trials in which the visual angle of display changed size (regardless of the direction of change), as opposed to when it remained the same size, it was clear that AMA had much more difficulty when the size changed. Indeed, whereas on "change" trials, AMA's mean RT was 2209msec (SD = 161), which is 10 SDs above that of the controls for this condition (mean RT = 700; SD = 156), in the "no-change" condition, her mean RT was 1409msec (SD = 90), which is 5 SDs above that of the controls for this condition (mean RT = 661; SD = 141). To analyse these data in more detail, we performed an ANOVA on the raw RTs with group (AMA/controls) as a between subjects factor and final spread (large/small), change of spread (yes/no), and response (1/2 X's) as within-subjects factors. This analysis revealed that the group differences in overall RTs were statistically reliable [ $F(1,7) = 55$ ;  $P < .0001$ ]. More importantly, we found strong evidence that AMA did require relatively more time when the spread of the boxes changed than when it remained the same, as shown by the interaction of spread-change and group [ $F(1,7) = 229$ ;  $P < .0001$ ]. Also, according to this analysis, there were no statistically reliable differences [ $F(1,7) = 0.832$ ;  $P < .39$ ] in the final spread conditions, nor was there an interaction between this factor with spread-change [ $F(1,7) = 1.3$ ;  $P < .29$ ] or group [ $F(1,7) = 0.09$ ;  $P < .93$ ].

*Discussion.* AMA's comparable performance on the wide-spread and narrow-spread conditions suggests that she does not have a problem in attending to patterns that subtend a relatively large visual angle per se. Therefore, her simultanagnosia cannot be ascribed to a specific problem in allocating attention over a large region. Similarly, her impairment in this task cannot clearly be attributed to a problem in feature analysis. Instead, the fact that she re-

quired more time when the display size changed (regardless of the final size) is consistent with a problem in adjusting the size of the attention window. The spatial indexing hypothesis leads us to predict a problem in adjusting or directing attention when the spatial properties of the target stimuli (in this case, the size of the area occupied by the target) vary from trial to trial. Indeed, if this expected result were not obtained such account would have been ruled out.

### Experiment 8: Naming Letter Pairs at Varying Spatial Separations

One clear prediction from the spatial indexing hypothesis is that AMA should have difficulty shifting and adjusting the scope of the attentional window for visual targets seen at new locations. In contrast, scanning or spreading attention over a set of predictable areas and locations should not be affected (or at least not to the same degree) by an indexing deficit; in this case, attentional shifts and adjustments can be accomplished by top-down control mechanisms. A generic problem with the control of the speed of the attention window implies that AMA should have more difficulty with large separations between the targets than with small separations. In the following two tasks we compared the effects on performance of varying the spatial distance between two targets, while the predictability of the location of such targets was either high or low. The logic of this experiment was the following: If the unpredictability of changes in stimuli locations exacerbates the problem in controlling attentional shifts, regardless of the spatial separation between items, then we can rule out the possibility that either slowing of attention alone or a deficit in feature analysis alone is sufficient to account for the simultanagnosia.

*Methods.* The task we used was originally designed by Warrington and Shallice (1980) to determine whether letter-by-letter reading arises from a limitation of the visual angle that a patient can scan or attend effectively. We used a version of this task where a different letter was positioned at the beginning and end of a string of digits, which varied in length. We printed the letters and digits in Geneva

36-point bold, and ordered them pseudorandomly (i.e. randomly except that there could never be two identical letters in the same trial). We administered three conditions, in separate blocks. The first block had different length strings (from three to seven items; e.g. B62169L) shown in a random order; the centre of each string was always aligned at the centre of the screen. This condition, the “variable length” condition, had 8 trials for each string length, which produced a total of 80 letters to be reported in the entire task. The subject began a trial by pressing the space bar; 250msec later a string of symbols appeared for 150msec, which was then replaced by a blank screen. The subject was asked to type (in any order) the two letters at each end of the string, and to omit typing a letter if she did not see it. In the second condition the “fixed length” condition, two asterisks marked the positions where the letters would appear, and remained on the screen until the space bar was pressed (to initiate a trial). A new set of random letters was used, and only the longest and the shortest string lengths used previously (i.e. the ones with three and seven intermediate digits) were used. Again, strings were visible for 150msec, but string length was blocked for 20 consecutive trials (starting with the strings with 7 digits). In the third and last part of the experiment, the “gap” condition, a new set of random letters was used. The distance between the two letters and all aspects of the procedure were identical to those of the fixed string condition. However, in these trials no digits (distractors) appeared between the letters. Five control subjects were also given this task.

**Results.** In the, variable length condition, AMA correctly typed 62% of the letters, and committed more omissions (75% of all errors) than incorrect choices of letters. When an incorrect letter was typed, it was typically a letter that was visually similar to the target letter (e.g. F/E, C/O, Y/V, M/W). As shown in Table 1, the percentage of errors (regardless of error type) increased systematically with the length of the string of digits only for AMA, and not for the controls. We performed an ANOVA on the mean percent error data with group (AMA/controls) and string length (3, 4, 5, 6, and 7) as the independent variables. AMA's overall error

**Table 1.** *Frequency of Errors (Percentages) for each string length*

|          | <i>String Length</i> |    |    |    |    |
|----------|----------------------|----|----|----|----|
|          | 3                    | 4  | 5  | 6  | 7  |
| AMA      | 31                   | 56 | 75 | 69 | 81 |
| Controls | 3                    | 1  | 6  | 6  | 6  |

rate (mean % error = 62.2, SD = 19) was higher than that of the controls [mean % error = 4.5, SD = 5;  $F(1,4) = 214$ ;  $P < .0001$ ]. AMA's increase in error rate with length was greater than that of the controls, as confirmed by the interaction of group and length [ $F(4,16) = 20.5$ ;  $P < .0001$ ]. Given AMA's high error rate, the RTs were not analysed for this task.

Following Warrington and Shallice (1980), we would infer that AMA's performance demonstrates that she has difficulty controlling the angle of attentional scan and that such control deteriorates proportionally to increasing distances to be scanned. However, as we suggested, difficulty in rapidly scanning and adjusting the attention window may reflect a loss of indexing ability. Given the high uncertainty of location of the letters (the strings varied in length unpredictably and were centred on the screen), AMA would have to find by serial scanning the letters at both ends of the string (thus, omitting more letters with increasing lengths of the strings). If our interpretation is correct, we would expect AMA's performance to improve dramatically in the two fixed length conditions. Moreover, the gap condition should eliminate serial scanning of the internal digits as an available strategy and would force AMA to scan directly to a memorised location.

These manipulations did reduce AMA's deficit; she now reported a larger percentage of letters in both conditions (see Table 2). As evident in Table 1 versus Table 2 for the largest separation condition, whereas controls' error rates in the gap condition (2%) were reduced to one third of that of the variable length condition (6%), AMA's error rate was about 16 times smaller in the gap (5% error) than the variable length condition (81% error) and comfortably within 2 SDs of the controls' overall performance (controls' mean % error = 3.5; SD = 2.2).

**Table 2.** *Frequency of Errors (Percentages)*

| <i>String Length</i> | <i>Condition</i>    |          |            |          |
|----------------------|---------------------|----------|------------|----------|
|                      | <i>Fixed String</i> |          | <i>Gap</i> |          |
|                      | <i>3</i>            | <i>7</i> | <i>3</i>   | <i>7</i> |
| AMA                  | 18                  | 28       | 5          | 5        |
| Controls             | 2                   | 5        | 1          | 2        |

Similarly, AMA's error rates in the fixed condition (28%) were reduced to about one third of her error rate in the variable length condition (81%), whereas for the controls the error rate were comparable in the two conditions (5% and 6%).

Separate 2 x 2 chi-square analyses were applied to the percent error data for a letter separation equal to seven digits (i.e. the largest letter separation), with condition (variable/gap/ fixed) and group (patient/controls) as the independent variables. Only one analysis showed a reliable difference between AMA and the control subjects, in the predicted direction: AMA's performance improved from the variable to the gap condition [ $\chi^2(1) = 3.91$ ;  $P < .04$ ]. As is evident in Table 1 versus Table 2 (when looking at the largest separation condition), whereas controls' error rates in the gap condition (2%) were reduced to one third of the error rates in the variable length condition (6%), AMA's error rate was about 16 times smaller in the gap (5% error) than the variable length condition (81% error), and comfortably within 2 SDs of the controls' overall performance (controls mean % error = 3.5; SD = 2.2). The other Chi-square analyses (i.e. variable vs. gap at three digits distance and variable vs. fixed at either seven or three digits distances failed to reach significance; however, for these analyses, power was too small to accept the null hypothesis (whereas for the above described analysis of the variable versus gap conditions, the effect size  $\phi = 0.2$ , and power = .48; Cohen, 1988).

*Discussion.* These findings, taken together with those of the previous experiment, provide evidence that AMA has a deficit in spatial indexing. The results were not consistent with the hypothesis of a specific limitation with angle of scanning. At the largest letter separation (seven digits), when the lo-

cations of the letters were known in advance (or became known after some practice with the task), and serial scanning of the digits was not possible (gap condition), AMA's performance was greatly improved and, indeed, was within normal limits. However, when she had to name letter pairs at varying spatial separations, where spatial separations between the two letters changed randomly, AMA read much more poorly than the controls. In this task, only accuracy for the shortest string (three digits) was within normal limits. Possibly, short spatial gaps between letters allow them to be easily grasped by the attention window without having to look for their positions. Although AMA's performance in the fixed condition was clearly reduced compared to the variable condition, it was still abnormal. It is possible that the presence of digits next to the letters forced AMA to make use of a serial scanning strategy.

Finally, some aspects of AMA's performance in this experiment may also reflect the presence of a feature degradation deficit. Simultaneously present distractors may interfere more with AMA's processing than the controls', which can account for the increase in her error rate relative to number of distractors and her greatly improved performance in the gap condition. Nevertheless, by itself, a feature degradation deficit would have not predicted the decrease in performance with changing the letters' spatial separation. This result is, instead, clearly expected from a spatial indexing deficit.

### **Experiment 9: Cueing One Location within Stable Multiple Stimuli Arrays**

The previous results allow us to conclude that AMA's simultanagnosia does not result merely from impaired focal attentional mechanisms (i.e. double-disengagement, narrowing, or slowing). The evidence thus far leads us to infer that AMA has a problem with indexing spatial locations and, as a separate but concomitant deficit, she may also have a problem in rapidly extracting visual features. In the following experiment we explored the indexing problem further. We evaluated AMA's ability to process multiple stimuli in fixed spatial locations when one stimulus is briefly cued, as opposed to

when it is not cued or invalidly cued. We used an experimental paradigm based on that developed by Posner and other researchers (e.g. Egeth, Jonides, & Wall, 1972; Eriksen & Hoffman, 1973; Jonides, 1980; Posner, Nissen, & Ogden, 1978). If AMA can make efficient use of a single cue, we reasoned, this will result in measurable attentional benefits when the location of a target is validly cued, and costs when it is invalidly cued, compared to a neutral cueing condition in which the cue signals the appearance of the target but does not provide information about its location.

According to the hypothesis that a simultanagnosic can only search items one by one, such a patient should show clear benefits from a location cue when viewing displays with multiple stimuli (e.g. eight letters in fixed locations). However, in contrast to normal subjects, for such patients the benefits of cueing should be much greater than the costs. In fact, with several multiple locations to search, performance after invalid cueing should be very similar to or indistinguishable from that after neutral cueing. The notion of a spatial indexing deficit leads us to expect that, when stimuli locations are constant (so that they can be encoded and "visited" on the basis of top-down processing), invalid cueing would result in normal attentional costs. This prediction is based on the idea that an indexing deficit would not preclude the processing of multiple stimuli in parallel if the set of possible locations has already been encoded. Therefore, when a neutral cue warns that the target is equally likely to appear in one of multiple locations, the attention window may be strategically adjusted to subsume all the possible locations and the target identified much more efficiently than after invalid cueing (cf. Jonides, 1980).

*Methods.* We used a paradigm similar to that of Jonides (1980), and compared AMA's performance costs and benefits in this task to those of five normal control subjects. The stimulus display was composed of eight letters (Geneva 14-point bold) that appeared at eight evenly spaced locations on a imaginary circle 9cm in diameter, centred on the screen; the same eight positions were used in all trials. The task consisted of pressing one of two keys,

marked L and R, to indicate whether the display contained either the letter L or R. Only one of these two letters could appear on any given trial, and each appeared on 50% of the trials. The target letter was equally likely to appear at each of the eight positions. There were a total of 160 trials; 50% of the trials were preceded by a neutral cue, 35% by a valid cue, and the remaining 15% by an invalid cue. The locations of the valid and invalid cues were equally likely among the 8 possible positions, and the identity of the distractor letters varied randomly from trial to trial.

The subject initiated a trial by pressing the space bar, which caused a small cross (the fixation point) to appear at the centre of a blank screen for 200msec. Then either the valid/ invalid cue (a small arrow, 5mm long) appeared within the imaginary circle at a distance of 1mm from one of the eight letter's locations, or a small black star appeared at the centre of the screen (the neutral cue). After 150msec the cue disappeared, leaving a blank screen for 50msec, after which the array of 8 letters appeared and remained in view until a response was made. Figure 8 illustrates the position of a cue to the following letters display.

*Results.* Neither AMA nor any of the controls made an error. All subjects had clear performance costs and benefits depending on the cue type. As evident in Fig. 9, when compared to the neutral cue, subjects were slower after an invalid cue and faster after a valid cue. An ANOVA performed on AMA's data with cueing (valid, neutral, invalid) as the fixed effect and replications as the random effect revealed that the differences in RT across cueing conditions were statistically reliable [ $F(2,155) = 31.8$ ;  $P < .0001$ ]. Post hoc Scheffe's tests confirmed that the neutral condition differed from both the invalid ( $P < .0001$ ) and the valid condition ( $P < .0001$ ). Separate ANOVAs for each of the five control subjects showed the same pattern of differences between cueing conditions ( $P < .0001$  in all cases). We also performed a single ANOVA with group (AMA/controls) as the between-subjects factor on the raw mean RTs in each cueing condition. This last analysis revealed a reliable effect of group [ $F(1,4) = 8.0$ ;  $P < .05$ ]; AMA was slower overall

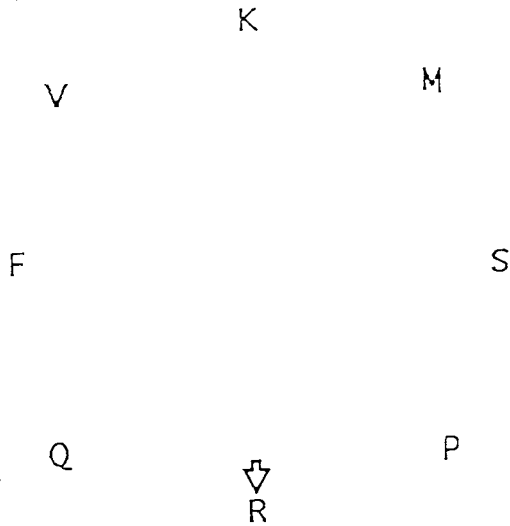


Fig. 8. Cueing one location: Arrow in valid position.

(mean RT = 3640msec; SD = 1082) than the controls (mean RT = 1455msec; SD = 788) in responding to targets. In addition, there was a reliable effect of the cueing factor [ $F(2,8) = 29.8$ ;  $P < .0002$ ] and of its interaction with group [ $F(2,8) = 4.9$ ;  $P < .04$ ]. The interaction reflected a smaller cost of invalid cueing for the controls [cost =  $1886 - 1521 = 365$ msec,  $t(1) = 2.2$ ,  $P < .06$ ] than for AMA cost =  $4761 - 3556 = 1205$ msec,  $t(1) = 4.6$ ,  $P < .0001$ ]. Benefits of valid cueing were of comparable size for AMA [benefit =  $3556 - 2601 = 954$ msec,  $t(1) = 3.9$ ,  $P < .0001$ ]

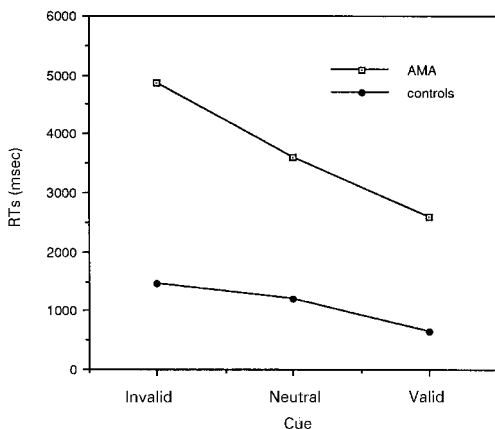


Fig. 9. Cueing one location: Mean RTs.

and the controls (benefit =  $1522 - 956 = 566$ msec,  $t(1) = 3.4$ ,  $P < .0008$ ].

*Discussion.* Although AMA was slower in general, her performance revealed the expected pattern of costs and benefits of cueing. Even within a “cluttered” display, she can make use of a single cue to direct attention to the target. More importantly, the fact that AMA performed much better with neutral cueing than with invalid cueing clearly demonstrates that she can attend over multiple stimuli, therefore, her simultanagnosia cannot be due to difficulty in processing multiple stimuli per se. This performance is also in sharp contrast to her difficulties with previous tasks in which targets appeared in unexpected locations, even when the arrays had a much smaller number of items. These earlier tasks required bottom-up visual searches, which would normally depend on spatial indexing mechanisms for their efficient control. However, the fact that the arrow cue was very small and close to the target position (as visible in Fig. 8, which illustrates the arrow cue's and letter locations), and that it appeared unpredictably in any of the eight locations, makes spatial indexing of the arrow essential for the efficient control of attentional shifts to a particular location. Indeed, the benefit from valid cues suggests that AMA could still index a single brief visual stimulus, albeit among a constant set of known locations. However, it is less clear why invalid cues produced more costs for AMA than the control subjects. One possibility is that AMA is more conservative (thus slow) in rejecting false targets because of her impairment in extracting the letters' features. Finally, the overall slowing of response (despite perfect accuracy), in this and other tasks, may also be the consequence of her exclusive reliance on a “reaching in the dark” strategy and/or, as previously established, slowness in choosing between two possible responses.

### Experiment 10: Encoding Spatial Relations

The ability to index several items in parallel may allow us to encode spatial relations efficiently between objects; logically, a spatial relation must involve two or more objects and locations. Indexing could lead to a rough spatial map that tells us where

to look and where we have already looked (cf. Ullman, 1984). Thus, if AMA has a problem with spatial indexing, we would expect her to be slow and inefficient when encoding spatial relations, and, when the viewing time is limited, to make many errors. Ullman (1984) and colleagues (e.g. Jolicoeur, Ullman, & Mackay, 1991) have stressed the importance of such visual routines in defining relations between multiple items or parts of an object. We surmise that the spatial indexing routine may be of particular importance for defining relations between multiple items, because focusing attention is necessary for the correct encoding of the locations of objects (Friedman-Hill et al., 1995; Robertson et al., 1997). Indexing would seem a prior step that makes it possible for the processing downstream to provide such explicit spatial information (cf. Logan, 1995).

### *Matching-to-sample Categorical and Coordinate Transformations*

Specifically, our analysis suggests that spatial indexing is a prerequisite for subsystems that compute and encode "categorical" and "coordinate" spatial relations (see Kosslyn, 1987; Kosslyn et al., 1989; Laeng & Peters, 1995). Categorical spatial relations are qualitative properties of the spatial juxtaposition of two or more objects (e.g. one is above, below, left, on, etc. another); in contrast, coordinate spatial relations specify quantitative, metric information about the juxtaposition of two or more objects (e.g. one is 2 inches from another). The two kinds of spatial relations are logically independent (Jacobs & Kosslyn, 1994; Kosslyn et al., 1989). Categorical spatial relations are a finite list of qualitatively different categories (mostly captured linguistically by prepositions; see Landau & Jackendoff, 1993; Miller & Johnson-Laird, 1976). Coordinate spatial relations, in contrast, extend continuously within a Euclidean/Newtonian-like framework. Evidence in support of the distinction between the two types of spatial relations has been provided by double dissociations between neural substrates supporting one or the other type of encoding (see, for reviews, Chabris & Kosslyn, 1998; Ivry & Robertson, 1998; Kosslyn, 1994). Specifically, categorical spatial relations rely on pro-

cessing in the left hemisphere (probably in part in the parietal cortex), and coordinate spatial relations rely on processing in the right hemisphere (probably in part in the right parietal lobe; see Kosslyn, 1994; Laeng, 1994).

Spatial indexing may be necessary for both types of processing; the locations of objects must be indexed before a spatial relation can be computed. In the absence of an indexing mechanism, encoding spatial relations will become laborious. Indeed, whereas we normally index locations in parallel, and hence can very quickly locate pairs of objects, with no such mechanism serial scanning will be necessary. Such processing will allow one to compute spatial relations, but with more effort than normal.

*Methods.* We tested AMA in an experimental paradigm similar to that previously used by Laeng (1994) in a study of unilateral stroke patients. In the first task, the subject initiated a trial by pressing the space bar. A 12 x 7cm black rectangle appeared at the centre of the screen, which framed the drawings of either two (in 70% of trials) or three (10% of trials) animals, or (in 20% of trials) of an animal and a common object that could support or contain the other object (these items probed spatial relations such as on/off; inside/outside). The animal and object drawings essentially constituted a scene (with a neutral background), in which the items were juxtaposed in a specified way. Each drawing could occupy an area no greater than 4cm in diameter. This initial image remained on the screen for 3sec, which was then followed by a blank screen for 4sec. Preliminary testing had shown that an exposure of 3sec was sufficient for AMA to name these pairs of objects. Thus, any problem observed would be unlikely to reflect a deficit in the recognition of the items, but instead must reflect a problem in the recognition of the spatial relations. Following the 4sec blank screen presentation, two frames, identical to the first, appeared on the computer screen, one above the other. One contained the original scene, but the other contained a scene with the same stimuli arranged differently; the different scene either varied from the original in terms of a coordinate spatial relation (e.g. objects that were 2cm apart were now 3cm apart) or a categorical spatial relation

(e.g. an object that was previously above another was now below it, without changing the distance between the items or their angular orientation). The subject was to indicate which frame contained the sample drawing by pressing one of two keys, marked T (for the top frame) or B (for bottom frame). The T key was positioned on the keyboard immediately above the B key. The test consisted of 64 trials that involved categorical transformations, 64 trials that involved coordinate transformations, and 14 trials that involved both types of transformation. The categorical trials included transformations of the following spatial relations: left/right (44% of trials), above/below (14%), in front/behind (14%), on/off (14%), and inside/outside (14%). The coordinate trials included the following metric relations, distance (52%), size (16%), global angular orientation (16%), and local parts angular orientation (16%). Trials in all conditions were ordered semirandomly (avoiding more than three consecutive runs of the same response or type of transformation). RTs were measured from the onset of the screen that contained the two frames.

**Results.** AMA committed 69 errors out of 142 trials (i.e. 49% of the trials) and performed virtually at chance levels in all three conditions (categorical relations error rate = 50%, coordinate relations = 51%, both relations = 36%). In contrast, the error rates for four control subjects was 10% for categorical and also for coordinate relations, and 5% for transformations of both relations. Figure 10 illustrates the findings for the categorical and coordinate spatial relations conditions. A chi-square analysis of the percentage of response with relation (both/categorical/coordinate) and group (patient/controls) as independent variables documented that there was a statistically reliable difference [ $\chi^2(2) = 18.6; P < .0001$ ]. Given AMA's high error rate, an analysis of the RTs would be difficult to interpret.

**Discussion.** It is clear from these findings that in spite of the fact that the first display could be examined for a full 3sec, this was not sufficient for AMA to encode appropriate representations of the spatial

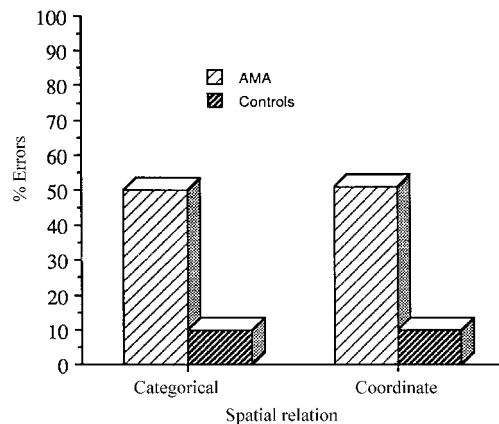


Fig. 10. Match-to-sample of spatial relations.

relations between items. Perhaps because the spatial relations could vary unpredictably along several dimensions, AMA could not prepare in advance to encode a specific relation. This problem could in fact arise from difficulties in attending to—or indexing—material spread over a wide region. Computer models developed by Kosslyn, Chabris, Marsolek, and Koenig (1992) and Jacobs and Kosslyn (1994) have shown that coordinate spatial relations are best encoded by input units that have large, overlapping receptive fields, and Kosslyn, Anderson, Hillger, and Hamilton (1994) have shown that attentional effects, and not hard-wired receptive field sizes, probably govern such processing. In general, AMA's problem appears to be at a relatively low level of analysis, as suggested by a spatial indexing deficit.

### *Linguistic Control of Spatial Attention*

If spatial indexing is an early bottom-up process that helps one to shift attention to the locations of novel objects, then the voluntary, top-down control of visual spatial attention should be unaffected in a patient whose lesion has selectively damaged the indexing mechanisms, but spared the subsystems that encode spatial relations (Kosslyn, 1994). Therefore, we would expect AMA to have no difficulty in comprehending and using linguistic cues such as “to the left of” or “above”, and so on.

Informal testing had demonstrated no sign of left/right confusion, and one of the investigators noticed that AMA, in looking out from the window of the 8th floor of William James Hall (at Harvard University) at the Boston skyline, could easily follow linguistic cues to gaze at specific sites (e.g. the green copper roof to the right of the State House Golden Dome, or the belfry to the right of the Hancock building). We also tested AMA in a short task in which verbal commands were given to the subject to position items in specific ways. The items were a quarter, a nickel, a dime, and a penny, which were placed in the subject's hands. There were 10 trials with different commands, each of which specified a spatial scenario (e.g. "place the quarter above the dime and the penny to the right of the quarter"). As expected, AMA was correct on all trials and performed the task without effort.

### PART 3: SEEKING EVIDENCE FOR A FEATURE DEGRADATION DEFICIT

Most lesions are not tailored to affect only a single function. Hence, we expect most patients to have multiple deficits, which may underlie even a single syndrome. Indeed, in our specific case, an impairment in pattern analysis and an impairment in spatial indexing are not mutually exclusive; each could produce separate but similar effects in several domains, independently of the other. Thus, in this final section we attempt to seek evidence for a problem in pattern analysis. As we saw earlier, although many of AMA's deficits are explained by a deficit in a spatial indexing mechanism, some of her difficulties were also consistent with problems in encoding patterns. For example, AMA's difficulties with a simple feature search is clearly interpretable both as a consequence of a deficit in spatial indexing or a deficit in encoding the shapes. In addition, in the task where letter pairs at varying spatial separations were to be named, the fact that the intervening digits interfered with naming the target letters may also suggest a problem with pattern analysis; similarly, her letter-by-letter reading is consistent with such a problem.

### Experiment 11: Matching Serially Presented Letter Pairs

Several researchers have suggested that simultanagnosia or letter-by-letter reading is a consequence of slowed processing of shape, which is caused by a "weakening" of the processes that analyse shapes (cf. Farah & Wallace, 1991). In this view, the perceptual system "locks onto" a single shape, which inhibits the processing of other shapes until the initial shape is fully processed (cf. Kosslyn et al., 1990; Kosslyn & Koenig, 1995). As described by Behrmann and Shallice (1995), patients can fail to report the first of two rapidly presented sequential letters. Behrmann and Shallice interpret this finding as a variety of backward masking, which occurs because the activation of the first letter is weak and easily disrupted by the activation of the second letter. Longer intervals between the two letters are needed for such patients than for normal subjects in order to avoid such masking.

The above considerations led us to utilise an experimental paradigm devised by Kinsbourne and Warrington (1962; see also Levine & Calvanio, 1978; Reuter-Lorenz & Brunn, 1990). In this paradigm, a patient is presented with one stimulus (e.g. a letter) in a fixed location and then, shortly after, sees a second stimulus (e.g. another letter) in another fixed location. The subject is asked to decide whether the two letters have the same name. This test would allow us to assess whether AMA's perceptual slowing and errors arose from difficulties in encoding shapes *per se*. In order to perform this task, it is not necessary to index the letters' locations because they always appear in fixed positions, which can be learned after practice. Thus, a problem in spatial indexing alone would not predict worse performance with *shorter* ISIs.

*Methods.* We showed AMA and eight control subjects two letters (72-point Monaco bold) that appeared sequentially on the computer screen inside two empty square boxes (with each side measuring 5cm). The boxes were separated by a 7cm gap, and each was positioned 3.5cm towards one side of the screen's centre. After pressing the space bar, a lower-case letter appeared for 50msec in the centre of the left box and, after a delay of 35, 70, 150, or

250msec, an upper-case letter appeared, also for 50msec, in the right box. Half of the time the two letters had the same name, and half of the time they did not. The subjects were to press one of two keys, marked S or D (for same and different), as quickly and accurately as possible. The task began with 10 practice trials (without feedback), followed by 80 trials (20 for each ISI, in a random order). RTs were measured from the offset of the second letter.

**Results.** Both AMA and the controls made more errors with shorter ISIs (see Table 1). AMA committed errors on 25% of the trials at 35msec ISI, 15% of the trials at 70 and 150msec ISI, and 10% of the trials at 250msec ISI. The control subjects, on average, committed errors on 9% of the trials ( $SD = 5.2$ ) at 35msec ISI, 5% of the trials ( $SD = 2.5$ ) at 70 ISI, 4% of the trials ( $SD = 2.4$ ) at 150 ISI, and 2% of the trials ( $SD = 2.6$ ) at 250msec ISI.

We were interested in assessing whether decreasing the ISIs led AMA to make proportionally more reading errors than the control subjects. Thus, we examined the disparity between AMA and the control subjects at each ISI, and found that AMA's performance was 3.1 SDs from the control subjects' mean at 35msec ISI, 4 SDs from the controls' mean at 70msec ISI, 4.6 SDs from the controls' mean at 150msec ISI, and 3.1 SDs from the controls' mean at 250msec ISI. Clearly, although her error rate was overall in the impaired range, the amount of difference in errors between AMA and the controls did not increase proportionally with shorter ISIs.

If we had only collected accuracy data, and ignored RT, we would have concluded that letter masking affected AMA and normal subjects in the same way. However, the RT data cast doubt on such a conclusion. On correct trials, AMA was slower (mean RT = 3560msec;  $SD = 1919$ ) than

the normal subjects [mean RT = 510msec;  $SD = 145$ ,  $t(158) = 14.2$ ,  $P < .0001$ ]. There were great differences between AMA and the subjects not only in the overall mean RT but also in its variance. In addition, both the control subjects' and AMA's RTs decreased with increasing ISIs (see Table 4). We applied the same analysis described earlier for error rates to assess whether these RTs differed disproportionately at short ISIs for AMA and the controls. It was clear that AMA was on average dramatically slower than the control subjects at every ISI: 39 SDs slower than the controls' mean at 35msec ISI, 36 SDs slower than the controls' mean at 70msec ISI, 26 SDs slower than the controls' mean at 150msec ISI, and 25 SDs slower than the controls' mean at 250msec ISI. Moreover, the difference in RTs was not constant, but rather was inversely related to the length of ISI. Indeed, whereas AMA showed a reliable difference [ $t(38) = 2.2$ ,  $P < .03$ ], the controls RTs were comparable [ $t(38) = 1.5$ ,  $P < .15$ ]. All the other comparisons showed reliable differences in RTs at each ISI step for both AMA and controls.

**Discussion.** The accuracy data revealed only that AMA was moderately impaired overall. In contrast, the RTs revealed a disproportionate change in performance over ISIs by AMA compared to the normal subjects. Clearly, AMA could not perform this task normally. Because of such specific abnormal performance with the change in ISI and because the locations of the targets were highly predictable, a spatial indexing problem is unlikely to underlie her difficulty with this task. A change in size of the attention window also could not account for the disproportionate difference in RTs at shorter ISIs. One possibility may be that AMA's

**Table 3.** Percentages of Error Rates at Each ISI for AMA and Averages (with SDs) of Control Subjects' Rates

|          | ISI(Msec) |        |        |        |
|----------|-----------|--------|--------|--------|
|          | 35        | 70     | 150    | 250    |
| AMA      | 25        | 15     | 15     | 10     |
| Controls | 9(5.2)    | 5(2.5) | 4(2.4) | 2(2.6) |

**Table 4.** Mean RTs (SDs) and at Each ISI for AMA and Control Subjects

|          | ISI(Msec)      |                |                |                |
|----------|----------------|----------------|----------------|----------------|
|          | 35             | 70             | 150            | 250            |
| AMA      | 4575<br>(2830) | 4282<br>(2311) | 3070<br>(1210) | 2841<br>(1737) |
| Controls | 564<br>(102)   | 523<br>(104)   | 497<br>(98)    | 456<br>(94)    |

attentional spotlight is “sluggish”, either in shifting or disengaging from an attended location to another; if shifts are initiated more slowly by her than controls, this would cause an increasing problem with increasingly shorter ISI. Yet, we saw previously that when AMA searched for a target among highly dissimilar distractors, her search was not simply slowed down but changed from parallel to serial. Thus, it would seem that the slowing of attention is more likely to reflect some other underlying dysfunction instead of being the primary cause. A likely candidate for the impairment in this task would then be a problem in analysing shape, which might reflect degraded visual features.

## GENERAL DISCUSSION

Patients have been described in the neurological literature who appear to have a basic problem in seeing multiple objects. Historically, this problem has been labelled *simultanagnosia* because although these patients may know that there are multiple objects present, they perceive only one object at any one time (simultaneously). However, this characterisation is vague as a description of a processing deficit, and it may fail to capture the essence of at least some varieties of the syndrome. After almost a century of investigations, it seems likely that there is no single account for all the types of deficits that have been grouped under this nosological label (e.g. see Farah, 1990). Our contribution, based on the study of case AMA, suggests another way in which some of the key features of *simultanagnosia* may arise. We have produced evidence that disruptions of spatial indexing may lead to several of the symptoms of AMA's *simultanagnosia*.

To summarise, in Part 1 we demonstrated that AMA was impaired in several classic neurological tasks that assess the ability to perceive multiple forms. These tasks were: (1) describing a complex scene (e.g. drawings in which the comprehension of an event depends on the integration of various objects' positions and actions into one thematic structure); (2) disentangling overlapping line contours, each depicting different common objects; (3) counting a variable set of items; (4) naming multiple objects seen “in a single glance” (i.e. within a

limited time frame). AMA was clearly impaired in all of these tasks, and also in other ones that can be characteristically disrupted in *simultanagnosia*, particularly reading. AMA evinced a slow, letter-by-letter strategy, similar to other *simultanagnosic* patients (e.g. Humphreys & Price, 1994).

In Part 2 we examined closely one aspect of *simultanagnosia* that has apparently not been investigated in previous studies: The patient's deficit in processing multiple items was clearly evident when they appeared in unexpected locations (e.g. in all those tasks in which from trial to trial the spatial properties of the multiple items were unpredictable), but was either nonexistent or marginally present when the target or targets appeared in fixed locations or within the same area of space. Thus, we are led to infer that AMA had an impaired mechanism that registers novel spatial information of candidate objects of attention. We hypothesised that this was a deficit in spatial indexing. To summarise this perspective, after the initial segregation of features and basic image properties, which results in figure/ground parsing and grouping, attentional mechanisms select the most salient figures (Sagi & Julesz, 1985a, b; Treisman, 1977). The locations of these selected items are then indexed; that is, “pointers” are assigned to each location to facilitate bringing the processing focus (attention window) directly to them. Once the processing focus has shifted, the input can be conveyed downstream to the areas that compute shape and spatial information (cf. Kosslyn, 1994). If such an indexing mechanism were to be compromised by a lesion, one could still identify and register the location of stimuli but would do so in a slavish manner. The speed of visual search for objects in new places would be particularly compromised, and the patient's visual scanning would resemble “reaching in the dark”; looking for objects of interest would be like making random hand movements or using a self-imposed systematic strategy that is blind to external cues.

The results also allowed us to argue that a number of alternative accounts for her performance are by themselves insufficient to explain the deficit. First, a general problem in switching (engaging and disengaging) attention to—or dividing it over—many locations (Bálint, 1995) is at best an

incomplete account. AMA was in fact able to direct her attention to locations where she expected the targets (e.g. when responding to a single cue). Although her control of attention was often slow and/or inaccurate (as indicated, for instance, by her overall higher error rate than controls when identifying letters that appeared rapidly in fixed locations), this problem could be a consequence of the loss of multiple spatial indices (whose purpose is in fact to direct attention). Indeed, if the primary deficit were a slow, "sluggish," attentional window, it would be difficult to account for the fact that the impairment was strictly dependent on the location of the targets. Moreover, in the visual-search "pop-out" task, a simple slowing of attention would predict a slow but nevertheless parallel search. Instead, AMA used a serial search strategy. In addition, AMA's loss of a pre-attentive phenomenon such as the subitising effect in counting objects is inconsistent with the hypothesis of a sluggish attentional window. In summary, these findings taken together put great strain on an account based on overall slowing of attentional control.

Second, a specific attentional deficit resulting in a narrowing of the scope of the attentional "spotlight" or "window" is an incomplete account. In a task in which the visual angle subtended by the distance between stimuli varied from trial to trial, there was no specific effect of widening as opposed to contracting such distance.

Third, we can exclude accounts that posit (1) a "weakening" of either the visual buffer (Coslett & Saffran, 1991), (2) visual awareness of shape under the attentional focus (Rizzo & Hurtig, 1987), or (3) a loss of resolution of the Treisman's master map (Treisman, 1988). If the first two accounts were correct, AMA's impairment should have extended to processing multiple stimuli regardless of the predictability of their spatial locations. In regard to the third account, a loss of resolution of the spatial map would perhaps predict a slowing of the visual search parallel function in Treisman's pop-out task but not a radical change of this into a serial search. Brain imaging showed little or no damage in the parietal lobes, where the spatially-organised "master map" is presumably localised (Friedman-Hill et al., 1995).

Fourth, we can exclude an account that posits a general problem in motor speed, since AMA's simple RTs were in fact faster than those of the control subjects. However, she was clearly slower than the control subjects in perceptual tasks (visual or auditory) that required choosing which of two keys to use for a response.

In Part 3, we collected evidence suggesting that AMA's difficulties were not simply caused by spatial indexing problems. In addition, she appears to have problems in analysing patterns. We found abnormal interference between the encoding of two letters when they appeared rapidly in succession. Because spatial information in this task was held constant for every trial (i.e. the letters to be compared always appeared in the same two locations and in predictable order), it is difficult to interpret the observed deficit in terms of a spatial indexing deficit. Thus, we conclude that AMA's problem in spatial indexing is compounded with a deficit in encoding patterns.

However, AMA's problem in parsing objects and encoding patterns was not apparent in all the tasks that would seem to require such operations. For example, AMA could disentangle an embedded abstract figure from a more global picture (i.e. the Hidden Figures test) and could draw accurately either from a model or memory. Her performance in the embedded-figures task was in stark contrast to her difficulty in disentangling overlapping figures, which may seem surprising. However, there is a key difference between the two tests. In the former, AMA had already memorised the target figure and was instructed to search for it. Thus, in the Hidden Figures task she may be using visual imagery to "augment" the input (cf. Kosslyn, 1994), whereas she would be unable to do so in the Overlapping Figures task because she had no foreknowledge of the stimuli.

In this report, then, we have shown that there are several aspects of the observed visual deficits that cannot be explained by problems in encoding patterns per se. Thus, it seems necessary to add a new type of cognitive impairment (namely, spatial indexing) to the list of mechanisms that, when impaired, may result in simultanagnosia. In particular, it is difficult to reconcile a feature degradation

problem with an impairment in encoding categorical and coordinate spatial relations. Rather, parallel indexing of separate items may be one important mechanism in the early segmentation of objects' locations in a scene and the selection of pairs of objects as "referent" and "relatum" on which ordered pairs of arguments (i.e. the spatial relations) can be directly computed (Miller & Johnson-Laird, 1976). In addition, the spatial indexing hypothesis led us to expect the difficulty AMA had in adjusting or directing the attention window when spatial properties (such as the area) of the target stimuli vary unpredictably. The feature analysis hypothesis would predict greater difficulty with fine-grained spatial variations of the stimulus than large ones, which we did not observe.

A deficit in spatial indexing also allows us to understand AMA's drawing skills, which were so remarkably unaffected. These abilities can be understood in the face of indexing problems, if (1) drawing from memory requires one to translate into movements an object structure that has already been encoded, and (2) during the act of drawing itself, the patient can move sufficiently slowly to allow her to use each part of the drawing as a reference point for the subsequent part. In addition, it is possible that visual imagery may augment the input by providing "virtual anchors" to where parts of the object need to be drawn. In short, the preponderance of top-down visual control in drawing would allow her to circumvent the limitations posed by a relatively low-level deficit in spatial indexing.

Finally, the neuroanatomical characterisation of AMA's lesion suggests only minimal (and unilateral) involvement of the dorsal areas, whereas extensive damage to the temporal lobes is evident. In addition, the presence of diffuse damage in the white matter is consistent with a disconnection between cortical processing areas. The behavioural data reviewed earlier would suggest that AMA's pattern recognition abilities were impaired, especially in data-limited conditions (e.g. tachistoscopic presentations). Moreover, we characterised her visual attention as "unanchored" from relevant cues in the input. It would then seem that, in her case, a spatial indexing mechanism has lost its guidance

from parsed regions of the image. Thus, we can speculate that the lesion to the ventral areas may have damaged processing that extracts form descriptors (i.e. the anchors themselves, on which indexes are created), and that a disconnection of the ventral areas from the dorsal areas may have prevented information about the anchors to become available to the dorsal areas, so affecting the control of attention.

Manuscript received 2 July 1996

Revised manuscript received 15 July 1998

Manuscript accepted 29 September 1998

## REFERENCES

- Allport, A. (1993). Attention and control: Have we been asking the wrong question? A critical review of twenty-five years. In D.E. Meyer & S. Kornblum (Eds.). *Attention and performance XIV*. Cambridge, MA: MIT Press.
- Atkinson, J., Campbell, F.W., & Francis, M.R. (1976). The magic number 4  $\pm$  0: A new look at visual numerosity judgments. *Perception*, 5, 327–334.
- Bálint, R. (1995). Psychic paralysis of gaze, optic ataxia, and spatial disorder of attention. (First published 1909). *Cognitive Neuropsychology*, 12, 261–281.
- Barbizet, J., & Cany, E. (1968). Clinical and psychometrical study of a patient with memory disturbance. *International Journal of Neurology*, 7, 44–54.
- Behrmann, M., & Shallice, T. (1995). Pure alexia. A nonspatial visual disorder affecting letter activation. *Cognitive Neuropsychology*, 12, 409–454.
- Benson, D.F., & Greenberg, J.P. (1969). Visual form agnosia. *Archives of Neurology*, 20, 82–89.
- Broadbent, D.D.E. (1958). *Perception and communication*. Oxford: Pergamon.
- Chabris, C.F., & Kosslyn, S.M. (1998). How do the cerebral hemispheres contribute to encoding spatial relations? *Current Directions in Psychological Science*, 7, 8–14.
- Cohen, A., & Ivry, R. (1989). Illusory conjunctions inside and outside of the focus of attention. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 650–663.
- Coslett, H.B., & Saffran, E. (1991). Simultanagnosia. To see but not two see. *Brain*, 114, 1523–1545.
- Costin, D. (1988). MacLab: A Macintosh system for psychology labs. *Behaviour, Research Methods, Instruments, and Computers*, 20, 197–200.

- Dehaene, S., & Cohen, L. (1994). Dissociable mechanisms of subitising and counting: Neuropsychological evidence from simultanagnosic patients. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 958–975.
- Distler, C., Boussaoud, R., Desimone, R., & Ungerleider, L.G. (1993). Cortical connections of inferior temporal area TEO in Macaque monkeys. *Journal of Comparative Neurology*, 334, 125–150.
- Donnelly, N., Humphreys, G.W., & Riddoch, M.J. (1991). Parallel computation of primitive shape descriptions. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 561–570.
- Duncan, J., & Humphreys, G.W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433–458.
- Duncan, J., & Humphreys, G.W. (1991). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 578–588.
- Egeth, H.E., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive Psychology*, 3, 674–698.
- Egeth, H.E., & Santee, J.L. (1981). Conceptual and perceptual components of interletter inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 506–517.
- Enns, J.T., & Rensink, R.A. (1992). Influence of scene-based properties on visual search. *Science*, 247, 721–723.
- Ericksen, C.W., & Hoffman, J.E. (1973). The extent of processing of noise elements during selective coding from visual displays. *Perception and Psychophysics*, 14, 155–160.
- Ericksen, C.W., & St James, J.D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, 40, 225–240.
- Ericksen, C.W., & Yeh, Y.Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 583–597.
- Farah, M.J. (1990). *Visual agnosia. Disorders of object recognition and what they tell us about normal vision*. Cambridge, MA: MIT Press.
- Farah, M.J., & Wallace, M.A. (1990). Pure alexia as a visual impairment: A reconsideration. *Cognitive Neuropsychology*, 8, 313–334.
- Friedrich, F.J., Walker, J.A., & Posner, M.I. (1985). Effects of parietal lesions on visual matching: Implications for reading errors. *Cognitive Neuropsychology*, 2, 253–264.
- Friedman, R.B., & Alexander, M.P. (1984). Pictures, images, and pure alexia: A case study. *Cognitive Neuropsychology*, 1, 9–23.
- Friedman-Hill, S.R., Robertson, L.C., & Treisman, A. (1995). Parietal contributions to visual feature binding: Evidence from a patient with parietal lesions. *Science*, 269, 853–855.
- Goodglass, H., & Kaplan, H. (1983). *The assessment of aphasia and related disorders*. Philadelphia, PA: Lea & Febiger.
- Harries, M.H., & Perrett, D.I. (1991). Visual processing of faces in temporal cortex: Physiological evidence for a modular organisation and possible anatomical correlates. *Journal of Cognitive Neuroscience*, 3, 9–24.
- Hausser, C.O., Robert, F., & Giard, N. (1980). Bálint's syndrome. *Canadian Journal of Neurological Science*, 7, 157–161.
- Hellige, J.B., Bloch, M.I., Cowin, E.L., Eng, T.L., Eviatar, Z., & Sergent, V. (1994). Individual variation in hemispheric asymmetry: Multitask study of effects related to handedness and sex. *Journal of Experimental Psychology: Human Perception and Performance*, 123, 235–256.
- Hellige, J.B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory and Cognition*, 17, 770–776.
- Holmes, G. (1919). Disturbances of visual orientation. *British Journal of Ophthalmology*, 2, 449–518.
- Howard, D. (1991). Letter-by-letter readers: Evidence for parallel processing. In D. Besner & G.W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition*. Hove, UK: Lawrence Erlbaum Associates Ltd.
- Howell, D.C. (1987). *Statistical methods for psychology*. Boston, MA: Duxbury Press.
- Humphreys, G.W., & Price, C.J. (1994). Visual feature discrimination in simultanagnosia. A study of two cases. *Cognitive Neuropsychology*, 11, 393–434.
- Humphreys, G.W., Quinlan, P.T., & Riddoch, M.J. (1989). Grouping processes in visual search: Effects with single- and combined-feature targets. *Journal of Experimental Psychology: General*, 118, 258–279.
- Humphreys, G.W., Riddoch, M.J., Quinlan, P.T., Price, C.J., & Donnelly, N. (1992). Parallel pattern processing and visual agnosia. *Canadian Journal of Psychology*, 46, 377–416.
- Inhoff, A.W. (1989). Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 544–555.

- Ivry, R.B., & Robertson, L.C. (1998). *The two sides of perception*. Cambridge, MA: MIT Press.
- Jacobs, R.A., & Kosslyn, S.M. (1994). Encoding shape and spatial relations: The role of receptive field size in coordinating complementary representations. *Cognitive Science*, 18, 361–386.
- Jolicoeur, P., Ullman, S., & Mackay, M. (1991). Visual curve tracing properties. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 997–1022.
- Jonides, J. (1980). Toward a model of the mind's eyes movement. *Canadian Journal of Psychology*, 34, 103–112.
- Julesz, B. (1981). Textons, the elements of texture perception, and their interactions. *Nature*, 290, 91–97.
- Julesz, B. (1984). A brief outline of the texton theory of human vision. *Trends in Neuroscience*, 7, 41–45.
- Kahneman, D., Treisman, A., & Gibbs, B. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, 24, 175–219.
- Kaufman, E.L., Lord, M.W., & Volkman, J. (1949). The discrimination of visual number. *American Journal of Psychology*, 62, 498–528.
- Kay, J., & Hanley, R. (1991). Simultaneous form perception and serial letter recognition in a case of letter-by-letter reading. *Cognitive Neuropsychology*, 8, 249–273.
- Kinsbourne, M., & Warrington, E.K. (1962). A disorder of simultaneous form perception. *Brain*, 85, 461–486.
- Kosslyn, S.M. (1987). Seeing and imaging in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148–175.
- Kosslyn, S.M. (1994). *Image and brain*. Cambridge, MA: MIT Press.
- Kosslyn, S.M., Anderson, A.K., Hillger, L.A., & Hamilton, S.E. (1994). Hemispheric differences in sizes of receptive fields or attentional biases? *Neuropsychology*, 8, 139–147.
- Kosslyn, S.M., Brown, H., Riffle, A., & Kim, I. (1998). *Age changes in the scope of visual attention*. Manuscript submitted for publication.
- Kosslyn, S.M., Chabris, C.F., Marsolek, C.J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulations. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 562–577.
- Kosslyn, S.M., Flynn, R.A., Amsterdam, J.B., & Wang, G. (1990). Components of high-level vision: A cognitive neuroscience analysis and accounts of neurological syndromes. *Cognition*, 34, 203–277.
- Kosslyn, S.M., & Koenig, O. (1995). *Wet mind: The new cognitive neuroscience*. New York: The Free Press.
- Kosslyn, S.M., Koenig, O., Barrett, A., Cave, C.B., Tang, J., & Gabrieli, J.D.E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 723–735.
- Kröse, B.J., & Julesz, B. (1989). The control and speed of shifts of attention. *Vision Research*, 11, 1607–1629.
- Krueger, L.E. (1978). A theory of perceptual matching. *Psychological Review*, 85, 278–304.
- Kreuger, L.E. (1983). Probing Proctor's priming principle: The effect of simultaneous and sequential presentations on "same-different" judgements. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 9, 511–523.
- Kuçera, H., & Francis, W.N. (1967). *Computational analysis of present-day American English*. Providence, RI: Brown University Press.
- LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 371–379.
- LaBerge, D. (1995). *Attentional processing. The brain's art of mindfulness*. Cambridge, MA: Harvard University Press.
- LaBerge, D., & Samuels, S.J. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology*, 6, 293–323.
- Laeng, B. (1994). Lateralization of categorical and coordinate spatial functions. A study of unilateral stroke patients. *Journal of Cognitive Neuroscience*, 6, 189–203.
- Laeng, B., & Peters, M. (1995). Cerebral lateralization for the processing of spatial coordinates and categories in left- and right-handers. *Neuropsychologia*, 33, 421–439.
- Landau, B., & Jackendoff, R. (1993). "What" and "where" in spatial language and spatial cognition. *Behavioural and Brain Sciences*, 16, 217–265.
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 451–468.
- Levine, D.N., & Calvanio, R. (1978). A study of the visual defect in verbal alexia-simultanagnosia. *Brain*, 101, 65–81.
- Lezak, M.D. (1976). *Neuropsychological assessment*. New York: Oxford University Press.
- Logan, G.D. (1995). Linguistic and conceptual control of visual spatial attention. *Cognitive Psychology*, 28, 103–174.
- Lowe, D.G. (1987). Three-dimensional object recognition from single two-dimensional images. *Artificial Intelligence*, 31, 355–395.

- Luria, A.R. (1959). Disorders of "simultaneous perception" in a case of bilateral occipito-parietal brain injury. *Brain*, 82, 437-449.
- Luria, A.R. (1966). *Higher cortical functions in man*. New York: Basic Books.
- Luria, A.R., Praudina-Vinarskaya, E.N., & Yarbus, A.L. (1963). Disorders of ocular movement in a case of simultanagnosia. *Brain*, 86, 219-228.
- Mandler, G., & Shebo, B.J. (1982). Subitising: An analysis of its component processes. *Journal of Experimental Psychology: General*, 111, 1-22.
- Marr, D. (1982). *Vision. A computational investigation into the human representation and processing of visual information*. San Francisco, CA: Freeman & Company.
- McClelland, J.L., & Rumelhart, D.E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, 88, 375-407.
- McConkie, G.W., & Zola, D. (1986). Visual attention during eye fixations while reading. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 385-401). Hove, UK: Lawrence Erlbaum Associates Ltd.
- Miller, G.A., & Johnson-Laird, P.N. (1976). *Language and perception*. Cambridge, MA: Harvard University Press.
- Morris, R.K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 268-281.
- Mozier, M.C. (1991). *The perception of multiple objects: A connectionist approach*. Cambridge, MA: MIT Press.
- Neisser, U. (1967). *Cognitive psychology*. New York: Prentice-Hall.
- Newcombe, F. (1969). *Missile wounds of the brain*. London: Oxford University Press.
- O'Regan, J.K. (1981). The convenient viewing position hypothesis. In D.F. Fischer, R.A. Monty, & J.W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 289-298). Hillsdale, NJ: Lawrence Erlbaum Associates Inc.
- O'Regan, J.K. (1984). How the eye scans isolated words. In A.G. Gale & F. Johnson (Eds.), *Theoretical and applied aspects of eye movement research* (pp. 289-298). Amsterdam: North-Holland.
- Ostreicher, H. (1973). *Memory for unrelated sentences*. (Unpublished manuscript cited in Lezak, 1976.)
- Paap, K.R., Newsome, S., McDonald, J.E., & Schvaneveldt, R.W. (1982). An activation-verification model for letter and word recognition: The word superiority effect. *Psychological Review*, 89, 573-594.
- Pashler, H. (1995). Attention and visual perception: Analysing divided attention. In S.M. Kosslyn & D.N. Osherson (Eds.), *Visual cognition*, Vol. 2 (pp. 71-100). Cambridge, MA: MIT Press.
- Pashler, H., & Badgio (1987). Attentional issues in the identification of alphanumeric characters. In M. Coltheart (Ed.) *Attention and performance XII* (pp. 63-81). Hove, UK: Lawrence Erlbaum Associates Ltd.
- Peterson, A., & Zangwill, O.L. (1944). Disorders of visual space perception associated with lesions of the right cerebral hemisphere. *Brain*, 67, 331-358.
- Patterson, K., & Kay, J. (1982). Letter-by-letter reading: Psychological descriptions of a neurological syndrome. *Quarterly Journal of Experimental Psychology*, 34, 411-441.
- Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 817-833.
- Posner, M.I., Nissen, M.J., & Ogden, W.C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H.L. Pick & I.J. Saltzman (Eds.), *Modes of perceiving and processing information*. Hillsdale, NJ: Erlbaum.
- Posner, M.I., Walker, J.A., Friederich, F.J., & Rafal, R.D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience*, 4, 1863-1874.
- Price, C.J., & Humphreys, G.W. (1992). Letter-by-letter reading? Functional deficits and compensatory strategies. *Cognitive Neuropsychology*, 9, 427-457.
- Prinzmetal, W. (1981). Principles of feature integration in visual perception. *Perception and Psychophysics*, 30, 330-340.
- Rademacher, J., Galaburda, A.M., Kennedy, D.N., Filipek, P.A., & Caviness, V.S. Jr. (1992). Human cerebral cortex: Localization, parcellation, and morphometry with magnetic resonance imaging. *Journal of Cognitive Neuroscience*, 4, 352-374.
- Rapp, B., & Caramazza, A. (1991). Spatially determined deficits in letter and word processing. *Cognitive Neuropsychology*, 8, 275-311.
- Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology*, 33A, 351-373.
- Reuter-Lorenz, P., & Brunn, J.L. (1990). A pre-lexical basis for letter-by-letter reading: A case study. *Cognitive Neuropsychology*, 7, 1-20.
- Rensink, R.A., & Enns, J.T. (1995). Pre-emption effects in visual search: Evidence for low-level grouping. *Psychological Review*, 102, 101-130.

- Rizzo, M., & Hurtig, R. (1987). Looking but not seeing: Attention, perception and eye movements in simultanagnosia. *Neurology*, *37*, 1642–1648.
- Robertson, L., Treisman, A., Friedman-Hill, S.R., & Grabowecky, M. (1997). The interaction of spatial and object pathways: Evidence from Bálint's syndrome. *Journal of Cognitive Neuroscience*, *9*, 295–317.
- Rousseaux, M., Delafosse, A., Devos, P., Quint, S., & Lesoin, F. (1986). Syndrome de Bálint par infarctus biparietal: Analyse neuropsychologique. *Cortex*, *22*, 267–277.
- Rubin, J., & Kanwisher, N. (1985). Topological perception: Holes in an experiment. *Perception and Psychophysics*, *37*, 179–180.
- Sagi, D., & Julesz, B. (1985a). Detection versus discrimination of visual orientation. *Perception*, *14*, 619–628.
- Sagi, D., & Julesz, B. (1985b). "Where" and "what" in vision. *Science*, *228*, 1217–1219.
- Santee, J.L., & Egeth, H.E. (1982). Do reaction time and accuracy measure the same aspects of letter recognition? *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 489–501.
- Talland, G.A. (1965). *Deranged memory*. New York: Academic Press.
- Taylor, E.M. (1959). *Psychological appraisal of children with cerebral defects*. Cambridge, MA: Harvard University Press.
- Thaïs, L., & De Bleser, R. (1992). Visual agnosia: A case of reduced attentional "spotlight"? *Cortex*, *28*, 601–621.
- Treisman, A. (1977). Focused attention in the perception and retrieval of multidimensional stimuli. *Perception and Psychophysics*, *22*, 1–11.
- Treisman, A. (1988). Features and objects: The Fourteenth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology*, *40A*, 201–237.
- Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97–136.
- Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, *95*, 15–48.
- Tsal, Y., Meiran, N., & Lamy, D. (1995). Towards a resolution theory of visual attention. *Visual Cognition*, *2*, 313–330.
- Ullman, S. (1984). Visual routines. *Cognition*, *18*, 97–159.
- van der Heijden, A.H.C. (1975). Some evidence for a limit-capacity parallel self-terminating process in simple visual search tasks. *Acta Psychologica*, *39*, 21–41.
- van Zomerén, A.H. (1981). *Reaction time and attention after closed head injury*. Lisse, The Netherlands: Swets & Zeitlinger.
- Wang, Q., Cavanagh, P., & Green, M. (1994). Familiarity and pop-out in visual search. *Perception and Psychophysics*, *56*, 495–500.
- Warrington, E.K., & Rabin, P. (1971). Visual span of apprehension on patients with unilateral cerebral lesions. *Quarterly Journal of Experimental Psychology*, *23*, 423–431.
- Warrington, E.K., & Shallice, T. (1980). Word-form dyslexia. *Brain*, *103*, 99–112.
- Watson, D.G., & Humphreys, G.W. (1987). Visual marking: Prioritising selection for new objects by top-down attentional inhibition of old objects. *Psychological Review*, *104*, 90–122.
- Weigl, E. (1964). Some critical remarks concerning the problem of so-called simultanagnosia. *Neuropsychologia*, *2*, 189–207.
- Weintraub, S., & Mesulam, M.-M. (1987). Right cerebral dominance in spatial attention. Further evidence based on ipsilateral neglect. *Archives of Neurology*, *44*, 621–625.
- Williams, M. (1970). *Brain damage and the mind*. Baltimore, MD: Penguin Books.
- Wolfe, J.M. (1992a). "Effortless" texture segmentation and "parallel" visual search are not the same thing. *Vision Research*, *32*, 757–763.
- Wolfe, J.M. (1992b). The parallel guidance of visual attention. *Current Directions in Psychological Science*, *1*, 124–128.
- Wolfe, J.M., & Bennett, S.C. (1996). Preattentive object files: Shapeless bundles of basic features. *Vision Research*, *37*, 25–43.
- Wolfe, J.M., Cave, K.R., & Franzel, S.L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 419–433.
- Wolpert, I. (1924). Die simultanagnosi: Störung der Gesamtaufassung. *Zeitschrift für die gesamte Neurologie und Psychiatrie*, *93*, 397–415.
- Yantis, S., & Johnston, D.N. (1990). On the locus of visual selection: Evidence from focused attention tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 135–149.
- Yarbus, A.L. (1967). *Eye movements in vision*. New York: Plenum Press.