NOTES

[1] In the appendix to *Reason, Truth, and History* (Cambridge, 1981) and in the appendix to *Representation and Reality* (MIT, 1988).

[2] W. V. O. Quine: 1983, 'Ontology and Ideology Revisited', *The Journal of Philosophy* **80,** 499–502: "If the subject is disposed to react to the presence of any and every cat in some manner in which he is not disposed to react to anything but cats, then I shall reckon the term 'cat' to his ideology".

[3] D. Davidson: 1989, 'The Myth of the Subjective', in M. Krausz (ed.), *Relativism: Interpretation and Confrontation*, University of Notre Dame Press, Notre Dame, Indiana, pp. 159–71. Quote is on p. 164.

[4] Ibid., p. 165.

[5] Ibid., p. 170.

[6] Ibid., p. 156.

[7] Ibid.

[8] Ibid., p. 164.

[9] I discuss this issue in my 1989: 'Wittgenstein on Meaning', *Grazer Philosophische Studien* **33–34**, 415–435.

[10] See my 1976: 'Substance Logic' (with E. Walther), *Boston Studies in the Philosophy of Science* **43**, 55–74 'A Plea for a New Nominalism', *Canadian Journal of Philosophy* **12**, 527–37 and my 1985 'Numbers', *Synthese* **64**, 225–39.

[11] The formalization of that statement involves a variable-binding operator, $x(\dots x \dots)$. It is, $l(J = l_1 \; \& \; M = l_2)$.

[12] J. Barwise and J. Perry: 1983, *Situations and Attitudes*, MIT, Cambridge, Massachusetts.

[13] See, e.g., 'Rationality and Believing the Impossible', *Journal of Philosophy* **80**, 321–38 (1983).

[14] See S. Kripke, 'A Puzzle about Belief', in A. Margalit (ed.): 1979, *Meaning and Use*, Kluwer, Dordrecht, pp. 239–83.

[15] I argued that point in my 1987: 'Truth and Some Relativists', *Grazer Philosophische Studien* **29**, 1–11.

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'WHAT' AND 'WHERE' IN THE HUMAN VISUAL SYSTEM: TWO HIERARCHIES OF VISUAL MODULES*

ABSTRACT. In this paper we focus on the modularity of visual functions in the human visual cortex, that is, the specific problems that the visual system must solve in order to achieve recognition of objects and visual space. The computational theory of early visual functions is briefly reviewed and is then used as a basis for suggesting computational constraints on the higher-level visual computations. The remainder of the paper presents neurological evidence for the existence of two visual systems in man, one specialized for spatial vision and the other for object vision. We show further clinical evidence for the computational hypothesis that these two systems consist of several visual modules, some of which can be isolated on the basis of specific visual deficits which occur after lesions to selected areas in the visually responsive brain. We will provide examples of visual modules which solve information processing tasks that are mediated by specific anatomic areas. We will show that the clinical data from behavioral studies of monkeys (Ungerleider and Mishkin 1984) supports the distinction between two visual systems in monkeys, the 'what' system, involved in object vision, and the 'where' system, involved in spatial vision.

INTRODUCTION

In humans, visual perception is the primary form of cognitive contact with the world around them. Looking out through the eyes, the brain acquires reliable knowledge of what goes on in the world and it uses this knowledge to guide behavior. Few people realize what an astonishing achievement this is. At least in part, this may be due to the fact that our conscious experience is usually a unitary one, while in reality objects in the field of view have discrete attributes such as place, form, colour, distance, size, or motion. What are the steps that our visual system goes through before we consciously perceive anything at all? Why are our perceptions usually reliable?

Viewed from a functional point of view the central problem of visual perception is how reliable knowledge of the world around us is extracted from a mass of noisy and potentially misleading sensory messages. Vision begins with a large array of measurements of the amount of light, or intensity, that is reflected from the physical surfaces of the environment onto the eyes' retinae. These measurements can be thought of as producing a large array of numbers that represent the

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intensity of light at different locations in the world. At the other end there is our conscious visual experience which tells us that the world is populated with three-dimensional things which we recognize effortlessly; we can manipulate them and we perceive where they are and thus we can avoid bumping into them. What happens in between? What is the information that one's visual system must make explicit? The computative answer to this question is that the logical organization of the problem must be discovered in terms of its independent constituent parts or modules.

The present view of how the brain analyzes the visual world is that modules, labelled as low-level vision, in the initial stages of processing proceed as a selective extraction of component features from the complete retinal image. The later visual modules, labelled as high-level visual functions, are characterized by processes that categorize visual information in ways which form the basis for the individual's appropriate interaction with the surrounding world. The main goal of these processes is to integrate the output of the early computations into meaningful visual categories and concepts.

The hypothesis that the processes involved in seeing constitute a set of relatively independent computational modules is a very powerful and important one. It is sustained by computational and evolutionary arguments, and more importantly by the fact that these modules can be experimentally isolated. Our ideas of what the modules of higher-level visual functions consist of are still speculative, but an attempt is made here to interpret the wealth of neurological-clinical observations in an information-processing framework, and to ask questions whose answers may be of significance in further investigations and may help us understand the specialization of the nervous system. In an earlier paper, we suggested the visual-processing modules beyond the visual discrimination level are of two types (Vaina 1985). One type we called 'feasibility', which embodies the specific mechanisms for solving specific visual problems, such as feature integration, perceptual categorization of textures or of shapes, object or spatial recognition, etc. The second type of processes we called 'routing', and their computational goal is to bring together the visual information required for the specific processes in the feasibility modules. Examples of 'routing' processes are the varieties of attention and memory. The early visual computations occur in parallel over the whole visual field and preattentively. In this paper we will not address the role of the routing processes in the visual computations that we describe. The focus of the present study is on the organization of the 'feasibility' processes in terms of two hierarchies of visual modules. One hierarchy, pertinent to 'what' is being computed, and the other heirarchy is pertinent to 'where' things are. We will bring neurological-clinical evidence for the existence of the 'what' and 'where' visual hierarchies of computational modules.

The idea of modularity is very attractive. As a general rule of thumb it is advantageous for complex-information processing systems to be constructed from a set of nearly independent parts. Thus, when a modification is required one does not have to change the whole system but need alter it only locally, and this is important for adapting the system to new conditions of operation. If the computation had a global character, if the modification had to occur in the process as a whole, then changes in one part would require simultaneous changes elsewhere which not only would be computatively expensive but would also make it difficult for the system to adapt itself to new conditions.

The same argument holds in an evolutionary framework (Allman 1987) where it is suggested that the formation of modules may have been produced by the replication of previously existing structures. The replication of existing structures appears to be a fundamental mechanism of evolution. For example, it has been argued that chromosomes' duplication would offer a reservoir of surplus genes from which new genes could arise. It is attractive to think that natural selection is restricted to natural genes and therefore the duplicated genes escaping this process accumulate mutations. This may enable the new genes to encode for new proteins which assume new functions. Using this as an analogy, it has been proposed that the development of new capabilities for processing afferent information could be sustained by the replication of cortical sensory representations. Thus, when a mutation results in a replication of a cortical area, this new area, through natural selection, could assume new functions while the original area continues to carry out its old function. This suggests that only biologically relevant changes are perpetuated. If a mutation occurs, the old function does not disappear and the new function will be adapted by the following generation only if it enhances the species' capability for survival. These areas can be thought of as processors, each independently and individually analyzing the information that it receives and then transmitting a suitable copy elsewhere. Thus a processor may respond to some information and not to other information. What is signal for one process may be noise for another, and this difference is deeply rooted in evolution. The discovery of the problems that each of these processors solves and the determination of their logical structure and place in the hierarchy of visual processing are issues at the computational theory level and belong to the feasibility modules. The channeling of the information to the processor specifically programmed to deal with it (focusing of attention) and the filtering out of what is noise or unimportant overload for a specific processing task are also issues at the computational theory level and are part of the 'routing' component.

COMPUTATIONAL THEORY OF THE EARLY AND INTERMEDIARY STAGES OF VISUAL PROCESSING

Vision starts with an intensity array in which two important types of information are contained: the intensity changes present and the local geometry. The first visual representation should make this information explicit. One's first observation is that the representation will not contain the intensity of light at each point in the world; it will contain only changes in the intensity, and this computational idea is consistent with what is believed to be the role of the early stages of processing in biological systems.

Usually changes in intensity result from physical changes in properties of the surface, such as reflectance, change in illumination, discontinuity in depth, or orientation of a surface. Marr (1976) showed that the types of intensity changes that occur in an image could be classified into a small number of general types that allow a concise description of an image in terms of low level symbolic assertions (the raw primal sketch) which have a high probability to reflect physical reality directly.

In natural images, intensity changes occur at various spatial scales and this requires the use of operators of different sizes. Marr (1982) lent evidence to the hypothesis that several channels, whose central frequencies are separated by approximately one octave, take part in producing this early representation which captures the local two-dimensional geometry of the visible surfaces. Marr and Hildreth (1979) have shown that the information required for the computations of the primal sketch is explicit in the zero-crossings contours of the Laplacian of the image after it has been smoothed by convolution with a Gaussian. The Gaussian optimally satisfies the constraint that intensity changes arising from physical objects are spatially localized at their own scale. One can then vary the size of the Gaussians. A larger operator captures the coarser structure of the image while a small operator will capture the fine detail; this kind of computation seems to be carried out in the multiple channels of the human visual system.[1]

Zero-crossings in each channel form a discrete database of symbols

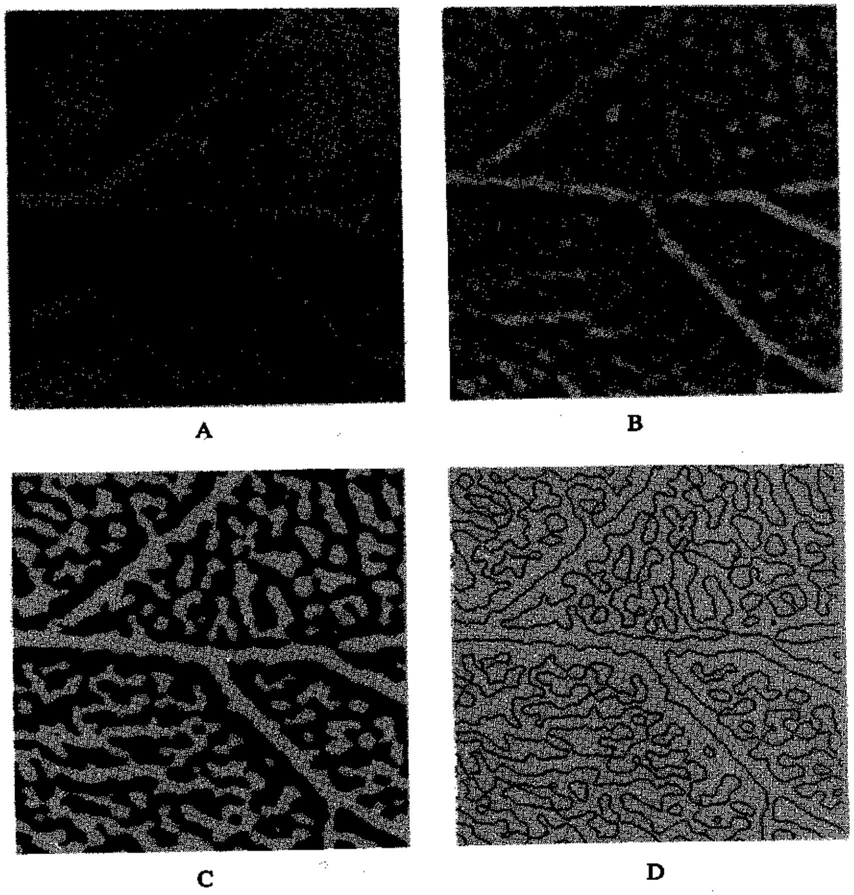

Fig. 1. Zero Crossing detection using V^2G (from Hildreth, 1980): (a) shows the image of a leaf, (b) shows the convolution with the V^2G operator ($w = 8$), with zero being represented by a medium grey, (c) positive values of the convolution are shown in white, and negative values are black, (d) only the zero-crossing contours appear.

which are used for further processes such as stereopsis, edge detection, or texture vision.

Physiological data suggest that cortical cells in the area 17, or the primary visual cortex, may be involved in detecting the presence of zero-crossing segments in the output of the $\nabla^2 G$ operator. The computations at this level of processing produce a set of feature points corresponding to the location of significant intensity changes (figure 1).

The next representation proposed by Marr is the full primal sketch which makes explicit object boundaries or contours, shadows, changes in texture, and specular reflections, obtained by using geometrical reasoning on the earlier descriptions and some limited higher-level knowledge (Torre and Poggio 1984). The result of applying the operations corresponds to the computation of the contour of physical objects.

The goal of the next set of visual modules is to derive a representation of the geometry of the visible surfaces. An object's visible surfaces are those parts that directly affect its intensity images, and for opaque materials this is the external surface of the object. Thus we must note that an image is 'caused' by the visible parts of the viewed objects, that the visible surfaces are only surfaces, and except in very particular cases (e.g., thin sheets) the description of these surfaces is distinct from the description of the objects themselves. The main effects that the visible parts have on objects can be related to variation in depth over the surface, variation of the surface orientation, and material composition; their explicit computation requires explicit processes which are defined on the primal sketch.

The special processes suitable for the acquisition of depth information generally involve the analysis of the parallax between the viewer and points on the surface viewed. There are different ways in which a visual system may accomplish this. One is by stereopsis where images from two locations are compared and positional disparities between corresponding surface locations are interpreted as variations due to differences in distance from the viewing position. Another way which may be used for obtaining depth information is motion analysis (Ullman 1977). If the surface is in movement relative to the viewer and its geometrical structure does not change over time, depth information for points on the surface can be recovered as a function of their distance from the viewer. Or, if it is known that the texture is uniform over a surface, depth can be computed from the measurement of the compression of texture pattern due to the perspective projection at different places in the image (Stevens 1979).

The various ways for deriving visible surface information are independent one from another. For example, the use of texture for determining

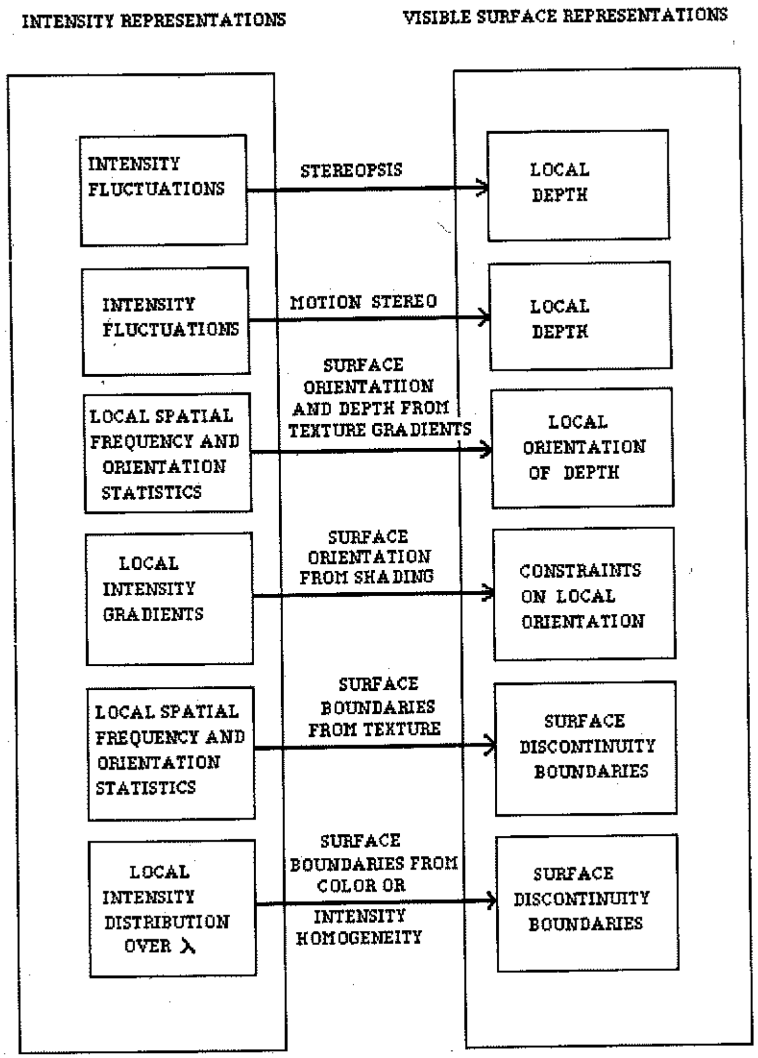

Fig. 2. Modules of early and intermediary visual information (Nishihara 1983).

orientation is different from the use of texture information for computing depth. One uses texture gradients, the other uses perspective projection. Thus the computation of information about visible surfaces can be viewed as finding solutions to a set of independent information processing problems, which all use information available in the primal sketch. The difficult and complex problem of finding information about visible surfaces was split into subproblems, or computational modules, whose solution is sought separately (figure 2).

The level of computation, which serves as an intermediary between the early detailed descriptions of the objects (the full primal sketch) and the three-dimensional representations suitable for their recognition, was termed by Marr and Nishihara (1978) the "2 and 1/2 dimensional sketch (21/2D sketch)". One of the main jobs of this representation is to maintain information from stereopsis, motion, and texture, in a faithful representation of the surface orientation and contours which is useful for the later processes such as those aimed at the recognition and manipulation of objects and space. The 2 1/2 D sketch describes surfaces locally and relative to the viewpoint. The overall goal of this intermediary processing level is the reconstruction of the three-dimensional geometry and the material properties of visible surfaces simply from using information that can be extracted from the primal sketch. The explicit surface description is referred to as the visible surface representation. The input information about the visible surfaces is provided by a number of specialized processes (figure 2) which are derived from the early symbolic representation of the primal sketch.

The visible surface representations delimit the boundary of pure perception and mark the passage to a more cognitive representation of the world which is the main concern of this study. Our hypothesis is that the content of these later representations must rely on the descriptions delivered by the earlier levels of visual processing. However, these later, more cognitive, representations have their own goal which is to recognize objects and space, and this goal will impose specific constraints on the design of these representations.

COMPUTATIONAL CONSTRAINTS ON THE DESIGN OF HIGHER LEVEL VISUAL REPRESENTATIONS

The importance of the computational theory cannot be overemphasized. In a trivial sense, having no computational theory means not understanding what the problem is at all. It should be stressed, however, that a purely theoretical or computational approach would not afford the whole answer; the intuitions needed for understanding biological information processing are not readily available. Only by wresting them from clinical experience can we see what questions need to be asked at the higher level of behaviour, such as visual recognition of objects and actions, for example, and develop a language in which to ask them.

We have seen in the previous section that the most important step toward the understanding of early vision was the discovery of the visual modules and of the processes that support their specific computations. For the higher-level vision, clinical neurological observations of patients with specific visual deficits have always been considered as a most valuable contribution to the understanding of the specific visual problems solved in humans. A basic question is whether the clinical observations embody assertions about problems that the brain solves when it perceives and interprets the world, and if so, what are they? This is a question at the computational theory level where vision is conceived as a hierarchy of semi-independent problems, each with its specific representations for describing the information that it handles and with specific processes which maintain and manipulate this information.

WHAT CAN BE LEARNED FROM THE COMPUTATIONAL THEORY OF EARLY VISION FOR ADDRESSING THE PROBLEM OF VISUAL RECOGNITION?

1. Properties of the physical world constrain the methods required to solve the problem. The insights of which assumptions are appropriate for a particular problem include insights from various disciplines, such as physics, physiology, psychophysics, and anatomy. The choice of the physical assumptions constrains the representations and the algorithms used to solve the problem. In the stages of vision which precede recognition, the physical assumptions refer to the general properties of matter; physical surfaces are solid, and locally rigid points on a surface occupy a single, well-defined location. For example, the derivation of surface information from motion-induced parallax is based on the assumption about surface rigidity (Ullman 1979).

In solving visual problems of higher level, such as recognition of shapes and their movements, or the representation of conceptual knowledge of space, additional assumptions useful for solving these types of problems must be added. These assumptions will constrain the design of the representations and of the algorithms. For example, shapes that were developed through growth and man-made objects tend to have well-defined axes of symmetry or elongation, and this is useful for reducing the redundancy of the visual image. "Tyger's . . . fearful symmetry" (Blake), is a welcomed regularity in the sea of noise of the sensory messages, and it gives one a hard fact to rely on in visual constructions. 'Biological motion', the patterns of the movement of animals and humans, is determined by the structure of the body and its physically possible deformations.

2. Representations make explicit specific information, and thus, when a representation is proposed one must be very clear about what are the properties that it will make explicit, and explore whether these properties are computed by the human visual system. Thus in the earliest visual representation, the zero-crossings make explicit significant changes of intensity in the image, and this is what we think the earlier stages of visual processing measure.

To discover the properties to be made explicit in representations at higher level visual functions, we turn to the observations of perceptual deficits after lesions in humans. An example is Warrington and Taylor's (1974) finding that lesions to the right parietal lobe impair the individual's capability of object recognition from an unconventional view (figure 4). Lesions to the left parietal lobe leave this capacity intact; such patients can demonstrate that they have recognized objects viewed from noncanonical views although their language difficulties may prevent them from naming the object.

These observations suggested (Vaina 1983) that on one hand, the representations of shapes are independent of the representation of the use and purpose of the shape and of its name. On the other hand, perception of shape is possible without necessarily implying its recognition as an object. Thus, for the perception of a shape one can rely only on the information that is made available by the earlier processes, and not involve higher level knowledge or context. Canonical views of shapes can be expressed computationally as views which allow the derivation of the shape's main axis (Marr and Nishihara 1978) or the extraction of the largest convex patches from the object's three-dimensional surface (Vaina and Zlateva 1988) and identifying such patches as object-parts (Biedermann 1985). Thus, the accessibility of a principal

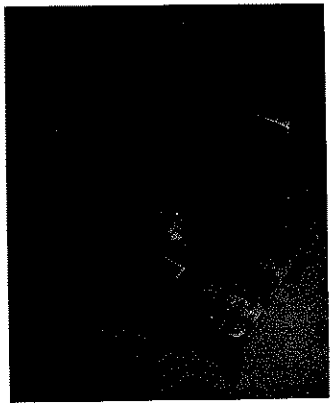

Fig. 3a.

Fig. 3b.

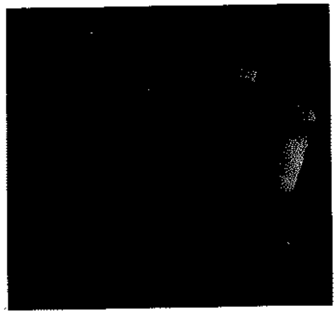

Fig. 3c.

Fig. 3. Object recognition from unconventional views (three views of a chair).

axis of objects, or of the largest convex patches, provides a basis for recognition. Such information must be made explicit in a representation whose goal is shape recognition.

3. Another important issue concerns the organization of the representation. The idea of scale is critical for a symbolic description of the significant changes in the image, and it has been shown that efficient description of different physical properties of images must be made at the appropriate scale. Not only is it necessary to describe information at different scales, but useful information about the physical world is obtained from the combination of descriptions across scales. The various levels of resolution are demonstrated consistently in physiology (the size of receptive fields) and anatomy (cortical maps), so this must be a basic property of the way in which the brain processes information, and hence it must be reflected in the organization of the representations of higher level functions as well (Vaina 1987).

4. The goal of a representation strongly influences its organization. The goal of the first levels of visual representations, the primal sketch and the 2 and 1/2 sketch is to provide a faithful report of the image. In order to achieve this, it performs detailed measurements of those changes that occur in the intensity of light in the image and of the properties of the visible surfaces. The requirement of faithfulness implies a representation centered on the viewer, that is a retinotopic or topographic representation of the world which changes with the change in location or position of the perceiver. Such viewer-centered representations have been proposed for the earlier stages of vision, and anatomic and physiologic findings support this organization. The goal of higher-level functions which involve recognition is consistency. Thus we are usually able to recognize objects independent of our vantage point, and this implies designing representations that rely on the intrinsic properties of the objects or space and are independent of the viewer's position. Thus, visual representations for the consistent recognition of objects and space must be object centered.

4a. The goal of consistency also requires the existence of a memory, or a catalogue, which must be accessed for recognition. Thus a main issue in the higher level representation is that of indexing into a catalogue based on attributes obtained primarily from the earlier visual computations.

4b. Faithful descriptions of the world by and large rely on data-driven processes whose goal is to squeeze as much information as possible from the image before one refers to information which is higher level than the current level of processing (Marr 1982). Consistency on the other hand, entails both data-driven, and goal or context-driven processes. Context and presuppositions play an increasingly important role as one progresses into the realm of cognitive processing of the world. Thus in a way we are returning to viewer-centered representations, but here the 'views' are goals for actions. The visual cognitive representations must then be organized as multiple descriptions of objects by their participation in different actions (Vaina 1985). A stick can be burned, and thrown, or broken. Each of these actions requires different properties of the object and these properties are often derived by different visual processes.

In the following section we shall provide evidence from neurological patients which supports the idea of modularity of functions. We shall see that the above computational constraints on the nature and organization of the representations can be incorporated as explanations for the nature of visual deficits. However, most of the neuropsychological experiments have not been designed with these computational theoretical ideas in mind and thus many address more complex questions than one would desire. We will show that the visual modules that can be obtained from the existing data can then be organized into two different systems, the object, or the 'what' and the 'where', or the spatial system. Such organization supports the distinction made by Ungerleider and Mishkin (1984) for the monkey's visual system.

EVIDENCE FOR THE MODULARITY OF VISUAL FUNCTIONS

The main focus of this article is on the modularity of visual functions, specifically on the contribution that the neurological literature makes toward the discovery of such modules.

The first task of the nervous pathways of the visual system is to transmit a suitably coded copy of the retinal image to the primary visual cortex where it is analyzed, and the results are then transmitted elsewhere. The visual image has multiple representations in different retinotopically organized areas, and although these visual areas are well delineated little is known about their function. It is known, however, that they differ in physiological character and in the resulting behavioral consequences when they're injured. It seems likely that these areas would serve different roles in visual perception, visuo-motor coordination, or perceptuo-cognitive relations as each encodes a different aspect of the visual image. Thus at the functional level these areas will be distinguished by the specific information they abstract from the image and the way in which they encode, access, and manipulate this information. The visual functions are not confined to these retinotopical areas but are extended further to visual association areas in the parietal, temporal, and frontal lobes.

The elegant work of Ungerleider and Mishkin (1984) provides evidence that, in monkeys, the different visual areas are hierarchically organized into two cortical visual pathways, one processing the information about 'what' the stimulus is and the other about 'where' it is. The first pathway consists of a multisynaptic occipito-temporal projection system which connects the striate, prestriate, and inferior temporal lobes. Its main function is visual identification of objects. This pathway is further connected to limbic structures in the temporal lobe and ventral parts of the frontal lobe, and as such it may affect cognitive associations and motor acts. The second pathway connects the striate, prestriate, and inferior parietal areas, and it is specialized for the visual location of objects. Subsequent connections of this pathway to the dorsal limbic and dorsal frontal cortex suggest the mechanisms employed in construction of spatial maps and visual guidance of motor acts. This distinction between two types of visual perception is not new; however, their cortical localization, as proposed by Mishkin's group, is novel. The previous work on these systems (Schneider 1968; Trevarthen 1968) considered their localization in the geniculostriate and tectofugal systems. As has been shown by Mishkin, it cannot be denied that the tectofugal system plays a role in spatial vision but in "primates it plays a subsidiary role".

MODULARITY OF VISUAL FUNCTIONS IN THE HUMAN BRAIN: NEUROLOGICAL EVIDENCE FOR THE EXISTENCE OF SPECIFIC VISUAL DEFICITS

All behaviour is a reflection of brain function; hence, disorders of behaviour must result from disturbances of the brain. For each behavioral phenomenon there exists a set of neural correlates that can, in principle, be observed objectively. We must credit Hughlings Jackson (1878) for the idea that a disease of the central nervous system can be regarded as a physiological experiment from which the principles of the

functioning of the central nervous system can be deduced. In order to study brain-behaviour relationships, we must be able to identify in a scientifically recognizable manner the properties of behaviour we are attempting to explain. Ideally we would like to be able to separate the modules involved in the tasks studied. This would enable us to eventually understand what is being computed, what are the elementary meaningful ingredients of the computation, and how they are related to the neuropsychological concept of double dissociation of function, as introduced by Teuber (1975, 1959).

> A double dissociation requires that a symptom A appear in lesions in one structure but not with those in another, and the symptom B appear with the lesions of the other but not of the one. Whenever such dissociation is lacking, specificity in the effects of lesions has not been demonstrated.

Teuber defines "symptom" as the patient's way of carrying out a task, which in my framework will correspond to the algorithm level.

Recognizing objects and our surroundings, or appropriately manipulating them, seem straightforward and simple tasks, and one is hard-pressed to imagine the multitude of complex processes that the brain must perform in order to carry them out. We have seen in the previous sections that current vision theories support the view that these processes occur at different levels and in different computational stages. The clinical evidence of the last hundred years reinforces the multistage view of visual processing, with the computational goals of each stage being characterized by several independent modules.

The major differentiation of deficits, suggested by Ungerleider and Mishkin's (1984) work in monkeys, is that between spatial and object recognition deficits. Taken with the anatomical evidence, this dissociation also provides compelling evidence for two different systems at work in visual recognition tasks in humans: one tells 'what' the information is and the other tells 'where' it is. Each of these systems carries out complex information processing tasks organized according to specific computational goals. In the following we shall review the neurological evidence for the existence of these two systems in the human brain.

WHAT IS IT?: FEATURE ANALYSIS

Appreciation of Colour and Form

Central achromatopsia is a selective loss of colour vision which occurs after damage to the bilateral inferior occipital lobe (Meadows 1974).

Mollon et al. (1979) stressed that colour information is still processed normally at the receptor level and that this information probably reaches the cortex intact, but the damage occured (Ratcliff and Cowey 1979) to the human equivalents of the areas V4 and V2 in monkeys. Hendricks et al. (1981) provided additional evidence for the existence of a visual defect of central origin associated specifically with the detection of coloured stimuli. They also showed that the chromatic and achromatic information are treated separately by the visual system. The patient described by these authors had normal fusion of random dot stereo-images (red and green random dot stereogram pairs) which is consistent with Lu and Fender's (1972) findings that such fusion involves luminance but not chromatic contrast. Efron (1968) described a patient who exhibited an isolated failure of *visual shape discrimination*, though he was able to use colour and size cues to identify objects in a given context. When the objects were removed from the familiar context, however, he was no longer able to name or recognize them. Specific disorders of form discrimination in patients with bilateral occipital-lobe lesions have been found in more recent studies (Warrington 1985; Vaina et al. 1989).

Deficits of Two-Dimensional Form Perception

Vaina (1987a) showed that patients with right occipital-temporal lesions were selectively impaired on tasks of form identification. The tasks required the ability to first extract a figure from the background on the basis of brightness, orientation of texture tokens, density, motion, or binocular stereopsis. Patients with right occipital temporal lesions were always able to obtain the coarse figure from the background but they failed to identify the exact shape of the figure. Thus, for example, previous evidence (Carmon and Bechtoldt 1969) indicates that global stereopsis assessed by Julesz's type of random dot stereograms is more impaired by right than by left hemisphere lesions. In our laboratory we showed that for stereopsis tasks in which the stimuli were taken from Julesz's (1971) random dot stereograms, patients with right occipital-temporal lesions could discriminate that 'something was there' and point to it in the random dots background, but they were unable to extract the exact two-dimensional figure. (The patients with right occipital-parietal lesions failed to see anything other than random dots in the stereopsis stimuli.)

These results demonstrated that in humans, similar to monkeys (Gross et al. 1985), two-dimensional shape perception is mediated by the posterior temporal area. Interestingly, our findings strongly suggest that in humans this computation is lateralized to the right hemisphere.

Deficits of Perceptual Categorization

In a study of patients who had undergone temporal lobectomy for the treatment of epilepsy, Milner (1958) found that those with right hemisphere lesions performed significantly worse than the left hemisphere group on a task requiring to identify anomalies in a sketchily drawn scene (McGill Anomalies Test, Hebb and Morton, 1943). She suggested that the right temporal lobe "facilitates rapid visual identification".

Warrington and Taylor (1978) proposed two serially organized categorical stages in their work on the visual recognition of objects. They demonstrated that the goal of the first stage is perceptual categorization, and it is carried out independently of the object's semantics. The second stage addresses the semantic categorization of the shape. In their study of three patients with visual agnosia, Ratcliff and Newcombe (1982) suggested that objects presented visually are identified on the basis of their visual characteristics alone and that characteristics from other modalities, and especially the particular names of objects, are only subsequently associated. Vaina conducted a detailed study of texture recognition (1987) which demonstrated that these two categorical levels are also involved in the processing of natural textures. Her study showed that the perceptual categorization stage is disrupted by right occipital-temporal lesions, whereas the semantic categorization stage is disrupted by lesions to the posterior left hemisphere. In her 'texture recognition' test the task was to match the visual texture of common objects, fruits, vegetables, or animals to the appropriate silhouette of the object. The pattern of deficits presented by the patients with right occipital-temporal lesions was interesting. When presented with the texture of a cauliflower, these patients may have identified it as the texture of a sheep. The texture of a pineapple was often identified as a snake, a honeycomb, or a fishnet. Patients with lesions to the right occipital-parietal area were not significantly impaired on this task. How is the information organized by the perceptual representation?

The second question addressed in this investigation was to determine the way in which the information is organized by the representations dealing with the recognition of textured surfaces. We shall turn now to the discussion of the results of the texture to object test with the goal of unravelling the sort of organization that the representation might impose on the information in its descriptions. Two categories of test stimuli were used in this experiment (see the companion paper in this volume). First, there were unstructured stimuli which allowed no further grouping or structuring. Unstructured textures, such as those of an orange skin or leather, are characterised by the simple distribution of some elementary tokens on the object's surface, and no further grouping or structuring of these tokens could be achieved by subsequent processing. On these textures, both classes of patients with occipital lobe lesions performed poorly, and in general, the right hemisphere patients were more impaired than the left. The fact that no laterality effect was obtained with occipital lesions confirms the physiological data that early visual processing is carried out equally in both hemispheres.

The early processes are concerned with the detailed analysis of the image in terms of its primitive features. The recognition of unstructured textures could be considered to be more difficult because their differentiation requires discrimination among the individual elements which implies processing at a very fine spatial resolution. Processing at a coarser resolution is not informative because the texture elements do not present any specific groupings which may be detected at larger resolutions.

The second group of textures exhibited a more complex structure (e.g., a pineapple skin or a cauliflower); and from looking at the errors produced by the right hemisphere patients in coupling the texture to the corresponding shape, a pattern emerged. The errors usually belonged to the same perceptual category with what would have been the correct answer (e.g., snake for pineapple). The errors produced by the left hemisphere patients were, as expected, more conceptual in nature. Thus, they tended to associate to the given texture the correct shape, but in naming, they often retrieved a superordinate category (e.g., vegetable for cauliflower, or animal for bear) or a functional property (I eat it when I go out to the restaurant). A possible explanation for these results is that the computation of textures may occur at several different levels. The first level involves simple statistical measurements on the entire surface to determine what is there and how it is spread. For example, when one is looking at an orange or a canteloupe, simple density distributions and statistics of their primitive component elements indicate that there is a simple, uniform structure. Further processing of grouping and categorization cannot extract additional information useful for recognition. However, if perceived at a very small, local scale, the two patterns could be differentiated because they have individual texture elements with different structures, although the specific distribution of the elements on the viewed surface is similar. Other textures, such as that of a pineapple or a cauliflower, are more complex. Here, grouping operations applied at different scales (spatial resolutions) may lead to the discrimination between various types of textures. Perceptually this implies that clustered texture elements could form regions which could be described visually at various scales. The scales used to describe the patterns occurring on a surface form a hierarchical description of the texture with the coarse, global statistical description on the top of the hierarchy and with descriptions using a finer scale at the bottom. This hierarchical description of the textures appears to be the organizing principle in a perceptual categorization which is independent of the object's specific form or of conceptual categorization of the object such as its function, its semantic category, or its name.

Thus, at the coarsest level, the texture of a pineapple, snake, fishnet, and honeycomb are very similar (Vaina 1985): all four have a general surface structure characterized by the regularity and the repetitiveness of a similar hexagon-like pattern. At a smaller scale, however, essential differences can be detected in the individual elements that form the pattern. These differences might be in the orientation or the exact shape of the component elements. Thus the fact that patients with lesions to the right posterior brain produced frequent errors which could be considered as belonging to the same perceptual category as the stimulus (sheep for cauliflower), appears to afford the explanation that these patients performed an incomplete processing of the stimulus. This processing was carried out at the coarser scales which were not sensitive enough to differentiate between textures belonging to the same perceptual class. Individuals with intact posterior right hemisphere could process the perceptual information adequately, but they might have failed to use this information for indexing into the representation of the corresponding object presented at the conceptual level. However, the response was rarely all or none; usually some residual information was preserved, and, exactly as in the cases described by Warrington (1975), this was of a more general sort.

The experimental results presented here suggest that texture information is represented at various scales organized from the more coarse to the more fine. This representation is constructed on perceptual criteria, independent of the meaning of the object. At a later stage of processing, however, these descriptions are put together with other visual and nonvisual, intermodal descriptions in the perceptually based component of the object's concept. To this, verbally mediated categorizations are added and thus the full concept of an object is achieved. The clinical data from patients with brain lesions suggested that perceptual categorizations are carried out specifically in the posterior right hemisphere, yet the association between these categorizations and the verbally mediated associations characterize left hemisphere functions.

What is the nature of the descriptions that might be useful for recognition? Taking the pineapple skin as an example, different levels of organization may need to be made explicit. These are: (1) the specific texture of the individual component shapes on the pineapple's surface, (2) the outline of these shapes, and (3) the organization of these shapes (i.e., the repetitive pattern they form on the surface).

Thus, two distinct levels of processing seem to occur in the description of textural patterns within a specific perceptual representation. First, the coarse overall texture is described without specific emphasis on the outline of the component shapes or their organization on the surface. The second level computes the local contours of the repeated shapes, such as the hexagon on the pineapple or snake's texture, or the long shape of the hair in the fur texture. The pattern of the repetition is also computed. Computationally, this entails a basic constraint on the design of a representation for visual textures (Marr, 1982); that is, texture change contours should be made explicit in the image since they identify the likely location of the discontinuities in surface geometry or surface structure, and these may guide recognition. This constraint is shared by the processes whose goal is the computation of the shape, as well as texture. But what can we say about such a representation?

The $V^2G = (d^2/dx^2 + d^2/dy^2)G(x, y) = (1 - 4r^2/w^2)e - 4r^2/w^2$ where $\nabla^2 G$ is a two-dimensional Gaussian function, w is the diameter of the positive central region of the operator and it is proportional to the Gaussian's space constant, and $r^2 = x^2 + y^2$, was applied on these images. As discussed earlier, the resolution of this operator, that is, the different scales at which the intensity changes are detected, depends on the value of w and is spatially localized. The smaller operators detect elements with finer detail which often presents too much detail to afford successful recognition. Stronger physical characteristics of the viewed objects are detected by all sizes of operators, and by and large this information is more useful for recognition. Paralleling the neurophysiological results, Marr and Hildreth (1980) proposed that the descriptions delivered by applying individual operators, like the individual channel descriptions (Campbell and Robson 1968), are combined into a single description of intensity changes in which contrast and width are made explicit. Thus, the information must be processed at different scales, and useful information is also obtained by combining descriptions across scales.

What would be the role of these various sizes of operators in the process of describing an object's texture, the texture of a pineapple, for example? Larger $\nabla^2 G$ operators will show the overall organization of the surface of the pineapple and perhaps the outline of the individual component shapes, but the textural characteristics of these component shapes would not be described. In other words, the size of the operator constrains the information made explicit by the process, and thus the information which is emphasized at any specific scale. The textured pattern of an object surface is essentially decomposed in zero-crossing segments which then provide the primitive texture elements. Similarities among these 'texture' primitives are sought at the next level of processing along some dimension, such as orientation, contrast, or size.

Thus, figure 4 presents the textures of a sheep fur and a cauliflower. When the image of a sheep fur is convolved with the G at various scales, one can see that the specificity of length and orientation of the individual component hairs are described more locally, and that larger operators will not emphasize this information. In fact when a larger operator is used ($w = 16$), only the rough groupings of large portions in the two textures are expressed. At that resolution, there is no essential difference between the cauliflower texture and the sheep texture. The differences occur at smaller resolutions where the individual hairs are made explicit in the sheep fur, yet are not found in the cauliflower convolutions.

After the first 'run' of the image with the Laplacian-of-a-Gaussian filters of different sizes, grouping processes must be used for the recognition of textures which present some structuring. The criteria for grouping may be suggested by the results of the statistical measurements on the image; the items with high frequency cause the texture analyser

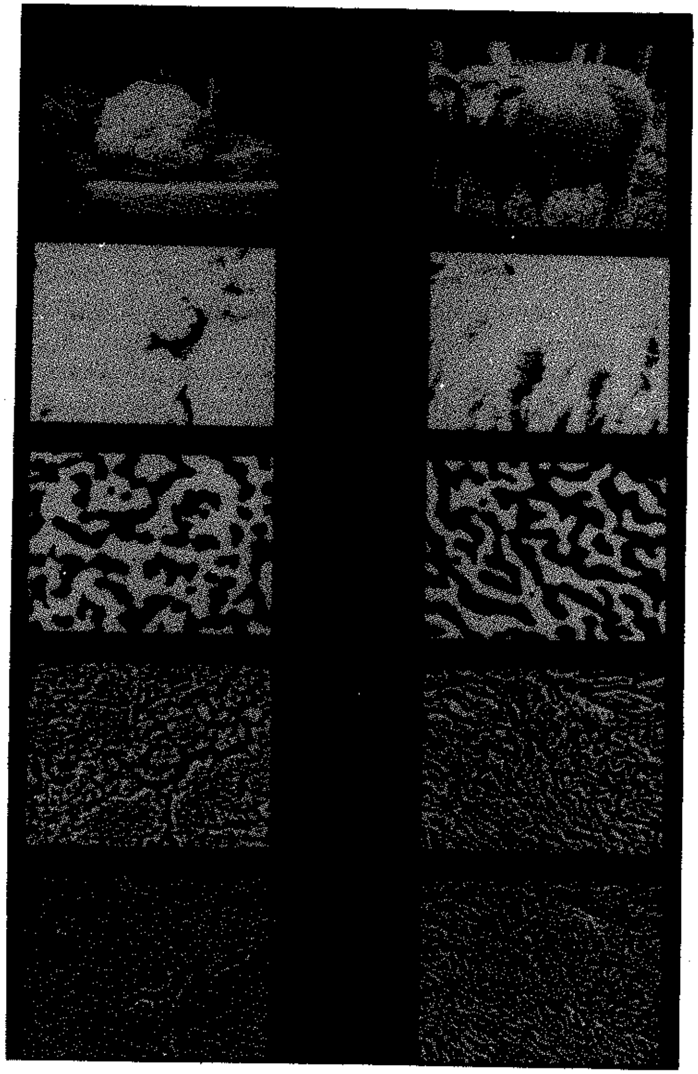

Fig. 4. The images of Figure 4 (sheep and cauliflower) convolved with a difference of Gaussian operator at three scales. The sign of the convolution is shown using white and black to indicate positive and negative regions respectively. The first pair (a1, a2) is with an operator with $w = 16$ pixels; (b1, b2) is with an operator with $w = 8$ pixels; and (c1, c2) is with an operator with $w = 4$ pixels. The convolutions are carried out in a pipelined convolver, designed and implemented by N. Larson and K. Nishihara.

to group them along the prevalent dimension. What the exact dimensions are on which this grouping succeeds still needs to be elucidated. However, it could be hypothesized that because the spatial coincidence at all the scales of zero-crossings in the Laplacian of the intensity filtered with a Gaussian mask reveals edges with specific orientations, and these edges have physical correspondence to the object, distinct from markings and shadows, it is possible that perhaps the further grouping processes would put together these edges in contours and then in the larger pattern repeated on the viewed surface.

The recognition errors exhibited by patients with lesions to the right occipital lobe interpreted in this framework lead to interesting testable hypotheses. The high incidence of confusing the texture of a pineapple with snake skin, honeycomb, or fishnet, suggests that the similarity of the component shapes of these patterns and the pattern of the repetitiveness of these shapes might play an important role in recognition. Indeed, in all three, the elementary shapes could be roughly approximated by a hexagon, which is then repeated regularly on the whole surface of the object.

A large operator of a low frequency applied to these images would produce similar results for all; differences among these textures would occur when $\nabla^2 G$ is used with a smaller width (w) which would process the images more locally. In other words, steep changes are seen equally by all sizes of operators, and these may determine the rough perceptual category of the texture. The hexagon-like component pattern and its repetitiveness of these shapes might play an important role in recognition. Indeed, in all three, the elementary shapes could be roughly changes capture the specific differences between textures with similar gross structure.

Thus the interpretation of the experimental results and the result of the computational interpretation consistently suggest that in the recognition process range and resolution are not both required simultaneously. High resolution, which allows the discrimination of the fine details on the textured surface, requires a short range for the process. Coarse resolution, which would account roughly for the overall organization of the textured surface, involves large range operators.

ASSOCIATIVE FUNCTIONS

Associative agnosia, is a syndrome in which "a normal percept has somehow been stripped of its meaning" (Teuber 1975). Lissauer (1880) defines visual agnosia as a deficit of the final conscious perception of a sensory impression, "the piecing together of separate attributes of a visual stimulus into a whole". The visual agnosias involving the 'what' system can be further differentiated into 'object', 'prosopagnosia', and 'colour' agnosias.

In *visual object agnosia*, the patient can see an object presented visually, he can draw it and match it accurately, but he cannot name it or demonstrate its use. The patient P.L. seen in our laboratory is an excellent case in point. He had severe deficits of recognizing objects or their use. In real life situations he was extremely handicapped, since he could not recognize objects nor could he identify their functions. Similar to many patients with visual agnosia, when the object was presented in a different modality, e.g., tactile, he could recognize and name it correctly. A common characteristic of visual agnosia is the inability to sort objects and pictures into categories determined by use (e.g., tools) or to match representations of the same object which differ only in scale.

These deficits led Newcombe and Ratcliff (1974) to suggest that objects must be identified at first only on the basis on their visual attributes, either by template matching or by visual feature extraction. In the absence of a unifying template, the visual features are used to search through a lexicon for objects with similar contour, size, and so forth. This hypothesis is appealing in that it may offer an explanation of why visual agnosia can be partial, such that an object can be recognized in its familiar surroundings (context) but not in an unusual environment, or it can be recognized when moved or rotated in the patient's visual field (Levine 1978). Recognition of all objects, or of only a specific subclass (Nielsen 1937, Warrington 1975) may be affected. Geschwind (1965) suggested that visual agnosia implies a disconnection between an intact left hemisphere language area and visual input resulting from an extensive destruction of the posterior part of the left hemisphere. Benson et al. (1974) reported an autopsy case of visual agnosia where a combined visual-speech and visual-limbic disconnection was suspected. Ross (1980) suggested that associative agnosia may result from a loss of the visual memories. He described two patients with bilateral inferior temporo-occipital lesions with severe memory deficits. One of these patients had prosopagnosia, achromatopsia, and spatial disorder, whereas the other patient's sole complaint was the inability to recognize recent acquaintances.

Static visual agnosia (Botez 1975) is a deficit of recognition of static objects or letters which can be recognized when they are presented in their characteristic movement. Botez attributes it to impairment to the geniculostriate system and the spared ability to localize and use movement for recognition through the tectopulvinar nonstriate system.

Animal experiments suggest that bilateral inferior temporal white matter lesions may block occipito-hippocampal connections and thereby prevent the formation of new visual memories and perhaps prevent the access into visual memory.

Prosopagnosia describes the inability to recognize familiar faces although often the patient may perceive faces normally (e.g., on formal testing discrimination and matching is normal). This impairment may involve associated deficits in recognition of other well-circumscribed categories such as types of trees, types of objects (Rondot and Tzaveras 1969), or types of animals. In their review of the visual agnosias, Haecan and Albert (1978) brought together a number of hypotheses and clinical facts which seem to imply that prosopagnosia would represent a visual memory disorder. Bilateral mesial occipito-temporal lesions are known to cause prosopagnosia, although there is an ongoing debate whether unilateral right posterior lesions alone can produce this deficit. Recently we have seen several patients with prosopagnosia. One patient, E.W., was totally unable to recognize members of his family by sight alone or to identify himself in a photograph. He performed well on the neuropsychological tasks of face recognition (Benton faces and Milner faces). He was also impaired in determining the age and gender in a photograph of a face. Interestingly, he had no deficits in determining facial expressions even in faces which he could not identify. As a side comment we note that patients with posterior right hemisphere lesions who failed to recognize faces also scored at a very impaired level on the neuropsychological tasks for face recognition. This leads us to hypothesize that failure on face recognition may occur for several different reasons. One possibility might be purely perceptual with deficits occurring either at the feature analysis level or at the 2 1/2 D sketch feature level where shading, texture, or surface is analyzed. The necessary basic visual information is lacking for identifying the face. Another possibility might involve memory deficits as well, and it is associated with bilateral occipital-temporal lesions extending into the hypocampus.

Damage to the occipito-temporal cortex produces agnosia for colour, or amnestic colour blindness (Wilbrand 1884), which consists of an inability to name or point to colours on command in absence of disturbances of colour perception. This disorder is not necessarily related to damage to the colour sense as the patient may perceive colours correctly. Colour agnosia may assume several forms. It may involve complete inability to name colours (Pick 1908, Goldstein and Gelb 1918), and as such it may be one-sided (Lewandowsky 1908). Gelb and Goldstein suggested that in colour agnosia, "there are not only defects in colour naming, but a disturbance in naming and indicating the colour of imagined objects". Colour agnosia may be in a degree such that some colours are confused one with another (e.g., yellow with red and orange, or green with blue) (Gelb and Goldstein 1924). Oxbury et al. (1969) distinguished two types of colour agnosia. One is colour agnosia associated with alexia without agraphia, which may be caused by a disconnection of the right visual center from left language centers (Geschwind et al. 1966). The patient can perform normally on tasks requiring processing to be carried out within one of these modalities, but he cannot produce intermodality associations (verbal with visual processes). In the second type of colour agnosia the deficit is in producing intramodality associations, e.g., visual-visual and verbal-verbal (Kinsbourne and Warrington 1964). This type of agnosia is considered to arise primarily from damage to the left parietal-temporal lobe.

Semantic Deficits of Texture and Object Recognition

Patients with posterior left hemisphere lesions have severe deficits on the semantic identification of objects and on naming. Generally, such patients are able to access the general category of the object, but they fail on the identification (by name or matching) of the specific object. I will show here examples of a similar deficit associated with posterior left hemisphere lesions, namely a failure on texture recognition, in spite of good perception of textures. Thus, patients with posterior left hemisphere damage tend to produce semantic errors on the texture recognition task discussed above. Instead of a cauliflower they would choose a head of lettuce which is in the same semantic category, 'vegetable', as the target. Instead of matching the texture of the tire to the appropriate silhouette, these patients often chose a truck, for example.

The empirical studies discussed in the previous section and the semantic deficits described above support Vaina's (1983) model of object recognition, which contains separate single modality descriptional representations for describing different aspects of an object, together with a functional representation useful for object manipulation and action comprehension. These various representations constitute separate processing modules within the model, occurring after the perceptual categorization but before verbally mediated categorizations. Their goal in the visual modality is to provide descriptions which are not cluttered with the detailed measurements delivered by the early visual processes but which capture the information in a form more immediately useful for recognition and manipulation.

It is possible that Warrington and Taylor's (1973) semantic stage consists in fact of two stages. The first occurs after the perceptual categorization (but at a preverbal stage), and its goal is to associate descriptions of the object's shape, texture, colour, and function in the visual modality, and the object's touch, smell, weight, taste, and sound in other modalities. This is consistent with the recent results of Warrington and Shallice (1984) which indicate that the semantic system is divided into material-specific components. Thus, if an associative stage of processing which collects together the information from the single modal descriptions of the object such as its weight, colour, shape and texture, followed the perceptual categorization stage, it would be conceivable that impairment of the perceptual categorizations or of their intermodal connections or incomplete perceptual processing could contribute to defective object recognition, and that the deficit may be selective depending upon the importance for recognition of those attributes which are not processed correctly.

The second stage of semantic processing is verbally mediated, and it contains the linguistic categorizations usually referred to as semantic memory (Tulving 1972; Smith, Schoben, and Rips 1974; Warrington 1975; Vaina 1985, 1983). Impaired recognition, including impaired object naming, may result from defective processing occurring in either of these preceding stages, or from deficits in their interconnections. It seems that the brain, after it takes the image apart, and before it puts it back together into the whole object again, goes through different stages of processing which are separately susceptible to damage. Thus, first the image is analysed in detail and its component characteristics are detected and symbolically described. This task is carried out in parallel equally in the most posterior parts of the right and left hemispheres (Warrington and Taylor 1979; Vaina 1985). Second, a perceptual categorization occurs where more global characteristics such as shape, texture, and colour are described in special purpose modality-specific memory systems. Processes such as indexing into these memories and searching are especially important here. The clinical studies of brain-injured patients suggest that the right hemisphere plays a dominant role in this stage of processing. Next, there is the associative stage where the perceptual characteristics are associated together in representations whose goal is recognition and identification of objects, and not merely their perceptual description. Here objects could be identified by their complex appearance and by their function or role in actions. Clinical neurological literature suggests that this stage is frequently carried out by the posterior left hemisphere. The verbal-semantic stage, also carried out in the left hemisphere, involves associating names with objects and this involves a verbally mediated categorization.

IS THE SERIAL ORGANIZATION OF VISION NECESSARY?

The above discussion suggests a serial organization of the visual processing:

* the analysis of an object according to its different dimensions,
* the computation of structural percepts according to the object's salient properties such as shape and texture,
* the association of all the specfic perceptual descriptions into a concept of the object, and finally,
* the verbal semantic stage where the object is associated with a name and is represented in a verbally mediated presentation.

Numerous examples suggest that this serial order, however, need not be strictly respected. Thus, for example, a few subjects with occipital lobe lesions, the subjects (H.B. and D.V.) who had a basilary artery infarction suggesting bilateral lesions and a large lesion of the right occipital lobe demonstrated by CT scan studies, when presented with the visual texture of an elephant skin said immediately that it was a skin. One of them (H.B.) picked out the silhouette of an orange; asked if it could be something else, he said that it "could also be a lemon or a green pepper, because all these have skin". When H.B. was cued and asked whether the correct answer could be an animal, he said: "let's see which animal has skin", and then decided that animals had fur, not skin, and thus it could not be an animal. Similarly, the subject I.M. – again with a basilary artery lesion – presented with the target of the elephant skin, said: "wrinkles, this must be thick skin". Then he looked at the choice of silhouettes and pointed to the elephant and said, "I cannot think of anything else".

It is possible that these subjects have associated as much as they have been able to process perceptually of the 'elephant skin texture', not with shape but directly with a verbally mediated semantic property encoded in a linguistic name, 'skin', which their by-and-large intact left hemisphere could handle correctly, and this name was used to index into the conceptual representation and search for objects which have 'skin'. The subject N.S., when she looked at the cauliflower texture, said 'curly, curly', and then pointed to the sheep silhouette.

We hypothesize that a semantic feature may also be associated with each specific type of texture (or object), and that this feature is encoded in language and is given a name (e.g., wrinkled, skin, curly, etc.). Is perhaps the semantic level more 'stable' and therefore more efficient for recognition? The perceptual descriptions carried out at the perceptual representation level of texture or shape processing are more accurate, and can deliver all the specific detail about the texture or shape. But perhaps this isn't always necessary for object recognition and manipulation; and it is possible that, in order to avoid combinatorial explosion of information, the passage from perception to cognition may involve a trade-off between accuracy and usefulness.

WHERE IS IT?

Studies from Zangwill's group (e.g., Patterson and Zangwill 1945) and from Hecaen's group (Hecaen, Ajuriaguerra and Massonet 1954) have shown that parieto-occipital lesions in man may impair spatial performance but leave intact performance on object features and object recognition. Visual spatial perception includes spatial relations, spatial aspects of shapes such as the perception of an axis of symmetry or elongation, object posture, and the perception of specific spatial features such as length and orientation of lines and motion analysis. We shall discuss these different aspects of spatial perception separately. First we will review deficits of spatial features analysis, then we will discuss the perceptual integration and categorization level, and finally we will discuss visual spatial agnosias.

FEATURES ANALYSIS

Visual Disorientation

This is a defective localization of objects in space in the absence of visual object agnosia. The elegant and thoughtful work of Holmes (1918, 1919) remains perhaps even today the most detailed and eloquent description of deficits in the visual exploration of space and their complex consequences for many spatial tasks. He reported six patients who suffered penetrating missile wounds to both posterior parietal areas and subsequently exhibited disturbances in orientation and space localization by sight, and were unable to estimate absolute and relative distances, lengths, sizes, and thicknesses. These patients could not differentiate which object was nearest and which farthest, which was most to the left or most to the right. They were unable to determine or compare size of objects. This resulted in patients bumping into objects when walking. All these patients exhibited the symptom of misreaching as well, which will be discussed later. It is important to note, however, that Holmes attributed the failure to reach for objects which were clearly perceived and identified, to defective spatial localization unlike Balint (1909) who considered it to be attributable to visual-motor disconnection.

Binocular Stereopsis

When discussing the 'what' or object visual system we presented evidence for the fact that right occipital-temporal lesions interfere with the ability to extract exact form from stereopsis, although the ability to perceive coarse figures remains intact. We also found that lesions to the right occipital-parietal lesions completely abolish stereopsis. The stimuli used in the experimental tasks were five random dot stereograms from Julesz (1971). The subject is asked to judge the apparent depth in the stereogram and to report whether a different pattern is visible from the surroundings and then to identify its shape. Patients with right occipital-parietal lesions were totally unable to perceive anything else than 'just dots' in the random dot displays. Similar results have been reported by Hamsher (1978) and Danta (1978).

Visual Motion Deficits

Riddock (1917), analysing actual records of war injuries to the occipital region, demonstrated that movement may be recognized as a special visual perception; that appreciation of movement returns before an object as such is seen; that recovery of vision for movement begins in the peripheral field. Riddock's analysis brings supportive evidence for the hypothesis that the elementary visual perceptions of light, of movement, and of colour, and of an object may be dissociated when specific visual areas have been injured. Zihl et al. (1983) reported a case, L.M., with severe disorder of movement perception in the absence of visual field deficit and amblyopia. L.M. had a massive lesion, but Zihl et al. (1983) suggest that the motion perceptual-deficit was due to bilateral involvement of the temporo-occipital cortex. Detection, performance, and localization accuracy were not impaired, nor was colour vision, form, and stereopsis. Moving objects were seen as present in one location and then in another but with little or no intervening movement. L.M. had severe difficulties in coping with the real world; thus crossing the street in the face of oncoming traffic was difficult because a car would seem far away and then suddenly it would be dangerously close. L.M. was unable to pour a cup of coffee without the risk of having it overflow, and this handicap could not be explained as an impaired depth perception since binocular stereopsis and monocular depth were both intact.

On formal testing, she had intact visual fields, normal visual acuity, colour perception, and form discrimination. However, she exhibited a specific disorder of movement perception, and she lacked pursuit eye-movements although the saccadic eye-movements were preserved.

Studies in our own laboratory (Vaina 1988; Vaina 1989) indicate that lesions to the right occipital-parietal area, but with the primary visual spared, produce specific deficits of visual motion analysis. Patients with such lesions were impaired on several motion tasks, such as relative motion, recovery of three-dimensional structure from motion, and speed discrimination. These patients showed no deficits on tasks of form and colour discrimination. We interpreted the results on the motion tasks as a defect at the level of motion integration, beyond the local motion measurement carried out by the early motion detectors in the area 17. More recent work from our laboratory (Vaina et al., in preparation) shows that such patients are also impaired on tasks of detecting motion signal in a global motion field. This is interesting since (Newsome and Pare 1988) by and large it was found that several aspects of visual motion interpretation are impaired in patients with right occipital-parietal lesions, whereas patients with right occipital-temporal lesions perform normally on such tasks.

VISUAL ASSOCIATIVE AGNOSIA FOR MOVEMENT

We define it as (Vaina, unpublished data) a deficit of recognition of objects in motion with the condition that when static the recognition of these objects is effortless and correct. We have studied in detail a patient, A.L., who had a stroke in the bilateral occipital-temporal-parietal region. Initially she was unable to recognize objects, colours, and faces. Several months later she recovered from these deficits, but she remained with a peculiar impairment of recognition of objects, faces, and animals when they moved. She found this very disturbing in her everyday living. Most striking was her complete inability to recognize animals presented as toy objects and photographs. Perhaps our concepts of animals are closely related to the pattern of their movement, which would explain A.L.'s deficit.

DEFICITS OF OBJECT RECOGNITION FROM INCOMPLETE INFORMATION AND FROM NON-CANONICAL VIEWS

Warrington and Taylor (1973) showed that patients with right parietal lesions could not identify objects presented as photographs taken from noncanonical angles. However, such patients do not have any deficits of recognition from photographs of the object's canonical (prototypical) view. Warrington interpreted these deficits as a failure of perceptual categorization, similar to the perceptual categorization of textures discussed in the previous section. The principles of categorization here are spatial. The object's major axis (Marr 1982) is used as a basis for the shape organization. Essentially, the right parietal patient group is unable to tolerate the deviation from the prototypical representation of objects.

A similar task, also difficult for the right parietal subjects, is Warrington's task of matching by physical identity. She suggests that this task requires the allocation to the same category of different descriptions of the same object. The different descriptions are expressed in viewer-centered representations, while it is possible that the stored memory of objects is in terms of object-centered representations. In this view, identification requires the ability to access an object-centered description. The access can be achieved through the object's axes of elongation or symmetry, or through identifiable features which then must be spatially organized.

Warrington and James (1967) have studied patients with localized cerebral lesions on Gollin's picture test, a graded difficulty task of identifying incomplete outline drawings of objects. They found that the right parietal group was significantly more impaired on this task than all the other patient groups tested.

Biederman (1985) carried out a similar experiment on the Gollin figures test in a group of normal subejcts. He presented a series of common objects (e.g., cup, glass, chair) which were degraded by deletion of portions of their contour. He observed that when contours were deleted at regions of concavity so that their end points when extended bridged the concavity, then the components were lost and recognition would be impossible. Thus, Biederman maintains that object recognition in cases of degradation or partial object presentation can be explained by the *principle of componential recovery*, which says that the components and their specific spatial arrangement must be identified for recognition to succeed. The identification of the spatial arrangement is facilitated more by some orientation than by others and this depends on the nature of the object and the parts in view. If the object has a major axis it would most likely serve as the basis for the spatial arrangement of the object parts. If a major axis is not available, but a functional part can be extracted, then it will serve to identify the object.

Simultagnosia

Wolpert (1924) described a case who suffered of an inability to recognize the meaning of a picture or a series of pictures even though the patient could correctly appreciate all the details. Kinsbourne and Warrington (1962) suggested that the defect was a limitation of simultaneous perception of visual forms which also accounted for the patients' reading disturbances. Wolpert's original patients could read only by spelling the words letter by letter. Recently we studied a patient with bilateral occipital-parietal lesions who showed distinct deficits of simultagnosia. On matching tasks, in which two simple geometrical figures were concomitantly presented on the computer screen, she was unable to perceive both at the same time. However, the patient's ability to identify the specific form of either of the two shapes was intact. Hecaen (1954) described a patient who failed to light a cigarette because when he perceived the match he did not also perceive the cigarette, and vice versa. This disorder may also contribute toward failure in perceiving more complex objects, or actions which were described earlier as deficits of integration of visual material whose individual features can be separately processed.

Thus we see that the 'where' system is involved in a specific aspect of the perception of objects, namely in the computation of the spatial arrangements of objects, parts, or in the accessing of the spatial reference of the object.

DEFICITS OF SPATIAL PERCEPTION, ORIENTATION, AND RECOGNITION OF SPACE

In early processing the organization of space is entirely egocentric, and it is based on the topographical representation of the retinal points in the cortex. Perception of space in this context involves perception of direction or orientation and relative localization in the coronal plane. It has been shown that the perception of direction is disturbed following injury to the occipital cortex. Occipital lesions may lead to a phenomenon (Potzl 1918; Goldstein and Gelb 1918; and Bender 1939) of creating a new center of spatial orientation which leads the individual to orient himself to this new center which he assumes lies ahead of him. Thus he will point erroneously or fail to grasp an object accurately. When the field of vision goes through a reorganization about the new center, the result will be a disturbance in spatial orientation.

More generally, the space around the individual can be considered to be composed of functionally different subspaces: the individual's own body, the grasping and reaching area, the ambulatory area, and the visual area. Different lesions in the brain may impair selectively the perception of subspaces. Spatial disorders relative to the individual's own body refer to errors in recognition, naming or pointing out on command various parts of his own body, disorders of the body image, and unilateral neglect. Critchley (1953) suggests that unilateral neglect may extend outward from the individual's own space, as in dressing apraxia (e.g., the patient may never put his right shoe on). Defects of body image, such as confusion between right and left parts of the body, may be due to the patient's inability to consider his body as an object of his surrounding space, and to relate its subparts one to another or to relate it as a whole to other objects.

Examples of disorders of functions in the grasping-reaching space are right-left disorientation, misreaching, and limb apraxia. The best-described of these disorders is that of misreaching under visual guidance, which Balint named "optic ataxia". Balint (1909) reported that a patient was unable to use his right hand to grasp or point at an object even though he was looking at the object. The patient could almost perform these tasks correctly with his left hand. Apraxia was excluded as responsible for this disorder because the patient could imitate with the right hand the movements of his left hand and was also able to perform acts which did not require visual guidance (e.g., buttoning his shirt, combing his hair). Balint suggested that the cause must be a disconnection between the visual and the motor centers. Damasio and Benton (1979) also described the reaching disorder in a patient with bilateral posterior parietal lesions who consistently missed objects in the nearby space but who could perform movements which did not require visual guidance (e.g., pointing to parts of the body, buttoning and unbuttoning of garments).

The most striking example of a functional disorder relative to the ambulatory space is impaired topographical sense, that is, the inability to find one's way around. This inability may be restricted to unfamiliar space, and thus to reading a map, or constructing one, or it may occur regardless of the environment.

De Renzi (1982) describes a patient who was unable to make localization on a city map but could correctly name its streets, public buildings, and gates. However, he could not specify the spatial relationship among the elements that he could verbally identify. Thus one must carefully differentiate between verbal knowledge of space and spatial knowledge of space. Another difference to note is that between memory for routes, or topographical arrangement, (e.g., one's house) and the ability to do mental spatial operations required in ambulation (Butters and Barton 1970).

We suggest that the handling of the ambulatory space is done in multiple coordinate systems. One system is object centered, desirable (Marr and Nishihara 1978; Vaina 1983) for shape and object recognition regardless of position in space; this may also be used for recognition in space. Another must be viewer-centered, needed for relating to the space around as a function of the subject's perception of space. A third coordinate system could be used to give a frame of reference for relating portions of the space one to another.

When the individual ambulates in space, all three systems must interact. One could conceive that following damage to the brain the use of one or more of these coordinate systems may be disturbed and this would result in a variety of deficits.

The last spatial area functionally relevant for the individual is that of the visual background. These deficits are common perhaps because, as Critchley (1953) suggested, this area is served only by one sensory modality vision. Thus, in the case of damage, there is no alternative system to take over the impaired functions. A careful analysis of the visual exploration tasks should reveal in part the complex architecture of the connections between the modules of the routing and feasibility components of the several examples of visual background deficits. We shall comment only on visual spatial neglect.

Visual Spatial Neglect

Chedru (1976) showed that neglect could be found in tasks which do not require visual input. Neglect should not be confounded with field defect, rather, it may be explained by the patient's neglect of some internal representation of space. Some authors suggested that neglect may be caused by a deficit of eye movements, but it has been demonstrated that spatial neglect can be found in visual processing tasks where it is unlikely that eye movements mediate performance (Posner et al. 1982).

Usually patients manifest visual neglect only on one side. This disorder has been reported under the name of unilateral neglect, visual hemi-inattention, or amorphosynthesis (Denny-Brown et al. 1952; Denny-Brown and Chambers 1958), or unilateral spatial agnosia. It can be easily detected in observing the patient's behaviour in his everyday activities. Denny-Brown and Bankers (1954) demonstrated that patients with unilateral inattention not only had visual disorientation in half-field, but also omitted material in one side of the body or failed to eat from one side of their plate. These authors believed that the deficit is a defect of spatial summation, "a loss of fine discrimination" or, in other words, a "disturbance of synthesis of multiple sensory stimuli". Earlier I presented this type of disorder as a spatial deficit of representation of one's body schema.

Bender and Furlow (1945) attribute neglect to the phenomenon of rivalry. That is, when stimuli are presented on both sides, the normal hemisphere will suppress the processing of the stimulus by the damaged hemisphere. Another possible explanation, advanced by Critchley (1953), Heilman and Valenstein (1972), Heilman (1979), and Watson et al. (1973), suggests that when neglect is multimodal it cannot be explained as a defect in any sensory modality, and it must be an attention deficit or, more precisely, a defect in the attention-arousal response (orienting response). They suggest that lesions causing the unilateral neglect syndrome cause a unilateral reduction of arousal, and not a reduction in the visual input. There is evidence that lesions in the inferior parietal lobule, or the dorsilateral frontal lobe, the cingulate gyrus and the mesencephalic reticular formation may each independently be responsible for unilateral neglect. Damasio (1980) suggested that in addition to lesions to the right frontal lobe, lesions in the basal ganglia cause "nonparietal neglect". Mesulam and Geschwind (1977) stressed that the capacity of the inferior parietal lobule in selecting stimuli of interest and maintaining them in the center of awareness is contingent upon the afferent inputs that it receives. Some of them come from the visual association cortex and transmit visual information already submitted to refined processing. Others come from the limbic and paralimbic cortex and convey the affective and motivational input for deciding which stimuli are significant for the individual. Others come from the thalamic, mesencephalic, and pontine nuclei, and it is likely that they would have an activating role.

These studies reinforce our distinction at the computational theory level, between routing and feasibility. A breakdown in either, or in their interaction, may cause the same observable deficit of hemi-neglect. The feasibility component is more 'matter-of-fact' and deals with visual information, yet perhaps the processing of this information must be directed by some 'routing' processes such as the control processes of motivation, affect, attention, intention, planning, etc. Deficits may also result from disturbances of processing in either of these components.

CONCLUSION

The theoretical framework for discussing observed deficits in the human visual system was the computational theory proposed by Marr (1976, 1982). In this framework, the main research goals are the discovery of the computational modules, their information processing substrate, and their relations in the overall visual perception of the surrounding world. The mechanisms by which perception is achieved are beyond the scope of the computational theory level.

We reviewed studies from the neurological literature which point out the existence of such computational modules in the human visual system. We have shown evidence for separate processing of object and spatial vision. Within each, we have shown that there are several stages, from the analysis of elementary features, to the viewer-centered descriptions of object and space, to the final object or space-centered descriptions which assure consistency and thus provide the basis for the cognitive processes, reasoning, planning, and linguistic communication. The discovery of modules and an understanding of their nature can be gained only by examining in detail the patient's behaviour on a large number of tasks. But it is not enough to find that a patient fails on a task, equally important is to find what tasks the patient can do. The decision about which tasks we should examine belongs partly to our knowledge of the mechanism, that is, how parts of the brain are connected and what their functions are; partly to the knowledge we have gained at the computational theory level, which tells us what must be computed in order to carry out information processing tasks; partly to the way in which the patient does certain things; and last but not least, partly to the informed intuition of the examiner.

By examining these issues within a theoretical and experimental framework, we shall be able to go beyond just marvelling at how extraordinarily complex brain functions are. We hope to begin to see what these functions are and how they process the visual world.

However, when we observe the visual behavior of patients, when we collect the experimental data, we have the "essential duty, common to all scientific workers, to distinguish the apparent from the real, the accidental technical from the preexisting and general fact. At the hour of judgment we ought to depersonalize ourselves and forget seductive prejudices, whether our own or others, and we must see things as if they were contemplated for the first time. And let us not fear the technical advances of the future because, if the facts have been observed well, they will endure although the interpretations may change" (Cajal 1954).

NOTES

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[1] The Laplacian is a nonoriented second derivative operator and thus zero-crossings in the Laplacian of the Gaussian filtered image correspond to the locations where the rate of intensity changes most at the scale of resolution determined by the width of the Gaussian.

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