Prosopagnosia as a Deficit in Encoding Curved Surface

Bruno Laeng[1] and Verne S. Caviness[2]

Abstract

■ RP is a case of "developmental" prosopagnosia who, according to brain-imaging segmentation data, shows a reduction in volume of a limited set of structures of the right hemisphere. RP is as accurate as control subjects in tasks requiring the perception of nonface objects (e.g., matching subordinate labels to exemplars, naming two-tone images), with the exception of one perceptual task: The matching of different perspectives of amoebae-like stimuli (i.e., volumes made of a single smooth surface). In terms of speed ("efficiency") of responses, RP's performance falls clearly outside the normal limits also in other tasks that include "natural" but nonface stimuli (i.e., animals, artifacts). Specifically, RP is slow in perceptual judgments made at very low (subordinate) levels of semantic categorization and for objects and artifacts whose geometry present much curved features and surface information. We conclude from these analyses that prosopagnosia can be the result of a deficit in the representation of basic geometric volumes made of curved surface. In turn, this points to the importance (necessity) for the normal visual system of such curved and volumetric information in the identification of human faces. ■

INTRODUCTION

Following brain damage, some patients seem to lose their ability to identify faces while, apparently, preserving the ability to identify other common physical objects. This disorder, named "prosopagnosia" (Bodamer, 1947) has attracted much attention. The prosopagnosic patients do not confuse faces for something else (e.g., a hat), but are unable to identify faces as of specific individuals' (e.g., Cole & Perez-Cruet, 1964; Beyn & Knyzaeva, 1962; Hecaen, Angelergues, Bernhardt, & Chiarelli, 1957). Such degree of specificity in a cognitive deficit linked to real-world knowledge is remarkable in itself, and together with separate types of evidence from neurophysiology, visual cognitive studies, and developmental cognitive psychology, the existence of this neurological syndrome strongly suggests the existence of a hard-wired, encapsulated "module" dedicated to the recognition of the visual appearance of co-specifics. Possibly, because faces are central cues to human identity and the biological relevance of such perceptual ability may be obvious (e.g., for kin recognition), special brain mechanisms devoted to the perceptual analysis of faces (similarly to the mechanisms for the analysis of speech) may have evolved (cf. Desimone, 1991; Johnson & Morton, 1991).

However, the issue of the specificity of face perception (or its deficit) is still debated. One central issue is whether those patients who have been reported to have just a difficulty in face identification truly have spared perceptual abilities for other classes of visual objects. Also, the converse issue is important, that is, whether object agnosics really can have completely normal face recognition skills. Until compelling evidence of such double dissociation is gathered, the whole contention about the existence of a domain-specific module is in jeopardy. Although some evidence seems to have been gathered for such reversed dissociations of deficits (e.g., Moscovitch, Winocur, & Behrmann, 1997; De Renzi, 1986), there are reasons to remain cautious. Gauthier, Behrmann, and Tarr (1999) have recently argued that a careful look at the literature on prosopagnosia fails to show unequivocal evidence for a disproportionate impairment for faces as compared to nonface objects. In their study, prosopagnosic subjects were requested to identify objects in several categories (both faces as well as nonface classes) at different levels of categorization (basic, subordinate, and exemplar). The study revealed the presence of clear impairments in the recognition of nonface objects, which were dependent on the manipulation of the level of categorization. Neurophysiological, single-cell studies have also led to the discovery of visual cells in monkeys that, after visual experience, show high selectivity for entirely novel and artificial classes of objects (i.e., paper clips). This finding casts serious doubts upon the logic that the object selectivity of a brain area implies the existence of functionally independent, endogenous, hard-wired "modules" (cf. Logothetis, Pauls, & Poggio, 1995). If brain functional imaging techniques have greatly helped to map out the neural substrate of face perceptual tasks (e.g., McCarthy, Puce, Gore, & Allison, 1997), faces and other objects of

[1]Harvard University, [2]Massachusetts General Hospital

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comparisons (e.g., flowers, fingers, and buildings) still greatly differ (see Tovée, 1998) in terms of associated knowledge and emotional content, people's expertise with the class, and last but not least, their shapes' geometry. Moreover, a few functional imaging studies have shown activation for other objects in the same putative "face" area (Gauthier, Anderson, Tarr, Skudlarski, & Gore, 1997) and similar, neighboring regions-of-activation for modern-age artifacts like chairs and houses (Ishai, Ungerleider, Martin, Maisog, & Haxby, 1997). Indeed, an aspect of the issue of no less importance is that, granting the existence of a truly face-specific module, how does it actually operate? That is, what kind of information does it extract, what coding does it use, in essence what sort of computations does it carry out. Faces, intuitively, seem to be a rather "eccentric" domain in terms of stimulus property (cf. Fodor, 1983). Indeed, it is unlikely that there exists in the brain one "all-purpose" recognition system that would provide a common code for describing both the subtle shape variations necessary for face identification as well as the coarse shape variations that are sufficient for common objects' identification. Faces and many natural and artificial objects may greatly differ in higher-order shape structure. Therefore, if research can specify what visual shape attributes and properties make faces, somehow, uniquely processed stimuli, this could reinforce the belief that the underlying brain mechanisms may also parcel or functionally separate from other brain areas.

The existence of a "pure" disorder remains doubtful, especially since the measures used in the assessment of the patients' visual deficits seem likely to be insensitive to the presence of other, albeit subtle, visual disorders. Among the weaknesses of the current methods is a widespread reluctance to use accuracy rates together with measures of efficiency (either quantitatively or qualitatively, that is, by response time measures or analysis of the patient's cognitive strategies, respectively). Needless to say, a performance that on the tables can result as accurate or within the range of performance of a group of matched controls may nevertheless hide serious abnormalities in other respects (Gauthier et al., 1999; Laeng, Kosslyn, Caviness, & Bates, 1999). The eventuality of speed/accuracy trade-off is haunting: Reports of patients performing better than their controls should be particularly suspected of a slowing of performance and, similarly, a high error rate may result from a rushed approach to difficult testing situations (possibly exaggerating a mild problem or a low range, yet normal, ability).

In relation to the issue of computational analysis, one way to characterize what the putative face module does would be to gather evidence that prosopagnosia can originate from damage to a mechanism that computes one or more visual properties hypothesized to be necessary for the normal perception of this object class. A research strategy for this type of investigation would be to seek covariation in deficits for several visual "kinds." Indeed, a definition in terms of necessary visual properties leads to a reformulation of the "goal" of the computation of such module below the level of a "folk psychology" category (i.e., "faces"). In this new perspective, the module may be better defined as the mechanism encoding "such-and-such visual property." As several cognitive scientists have noted (e.g., Pinker, 1997, pp. 273–274), the distinction between a perception module that recognizes faces and a module that recognizes kinds of objects with the geometry of faces is simply meaningless. This theoretical stance implies that anything special about a perception module is the kind of geometry it encodes. Evolutionary pressures could have shaped the brain's architecture towards optimizing the perception of those geometric properties that enable us to distinguish faces.

Theoretical Background

Each face has to be perceived as an ostensive cue to a unique state of things in space and time: a one and "irreplaceable" person. Remarkably, we can distinguish effortlessly the face of each one of our co-specifics, even those of identical twins. Identifying other objects at such low levels of taxonomy seems to be a more rare occurrence and this situation typically involves the association of an object with a person (e.g., my car, your bag, i.e., personal property objects). Indeed, intermediate levels of semantic identification constitute most of our cognitive appraisal of external objects and would seem the preferred entry-level to our knowledge system for natural kinds (Rosch, 1975). Moreover, subordinate labels for entry-level identification (e.g., naming immediacy) are typically found for members of a class that differ in shape (e.g., penguins and ostriches are preferentially named as such and not as "birds"; see Jolicoeur, Gluck, & Kosslyn, 1984). Faces are instead a visual class where perceptual similarity is extreme; yet their entry-level is the lowest in semantic taxonomy (Tanaka & Gauthier, 1997).

Because face identification requires a unique solution (i.e., that specific individual), it seems obvious that its underlying processing should be computationally different than that of recognizing "classes" of objects, or "kinds." In fact, the recognition of kinds, or "basic-level" recognition as it is often referred to, could be solved by encoding, storing, and matching "abstract" perceptual primitives. The task could be achieved by use of sets of nonaccidental properties (Kosslyn, 1994; Lowe, 1985) or structural descriptions made of primitives like generalized cylinders (Marr, 1982), contour-segments (Hoffman & Richards, 1984) or "geons" (Biederman, 1987, 1995). Instead, in order to recognize "individuals" or exemplars within the class, the encoding, storing, and matching of visual patterns must preserve a fair amount of perceptual detail if recognition has to be successful. In general, more perceptual detail would seem necessary for identifying an object as a member of a "subordinate" class than at a superordinate, more abstract, level (e.g., a species of dogs, a kind of apple, as opposed to merely "a dog" or "an apple"). The fine-grain level of description is clearly lost with abstract edge-based structural descriptions that specify the components (i.e., geons) of a shape and the qualitative spatial relations between these parts (e.g., left-of, top-of, larger-than, end-to-end-connected). Nonaccidental properties also capture exclusively the abstract relations between features of lines and edges (contour). The advantage conferred by the abstractness in these perceptual descriptions is that the object's structure can be captured in a way that remains invariant across a potentially infinite number of shapes that share the same primitives. What in space–time coordinates are indeed different objects can be grouped together as instances (tokens) of a perceptual category (a type or a "natural kind"). Another advantage of these types of structural descriptions is their ability to capture the identity invariance of one class of shapes despite its variation of projections (consider different viewpoints of a rigid shape—e.g., a chair—or changes in the intrinsic shape of a flexible object—e.g., a cat; Laeng, Shah, & Kosslyn, 1999). However, these types of structural descriptions could be adequate at most in capturing the "schema" of the face. Yet, a more fine-grain perceptual analysis of shape would seem to be required for subordinate, individual levels of identification than for the basic level. This increased perceptual scrutiny may require integrating together with edge-based information also spatial (metric), color, texture, and surface information (cf. Jolicoeur et al., 1984). As several researchers have proposed (e.g., Biederman & Kalocsai, 1997; Farah, 1995; Carey & Diamond, 1977), shape information used in facial representations may be holistic, surface-based, and metric, as opposed to information that is part-based, discontinuous, and qualitative (sufficient and, perhaps, more efficient for basic levels of identification).

Intuitively, faces are "objects" for which surface information is particularly important to recognition. We observe that faces are almost entirely made of a single curved/smooth surface (a visible, outer portion of an "ovoid," that is the human head) with multiple convexities and concavities (e.g., pits and ridges over the "mask" of the face). There are few exceptions to its unity or wholeness: the two embedded spheroid surface patches corresponding to the eyes and an almost shapeless (fractal-like) texture corresponding to the hair. A connected and bounded portion of space is considered geometrically as a smooth object (Koenderink & van Doorn, 1982). Although the appearance of a 3-D curved/smooth object can vary considerably with changes in perspective and to some degree with the muscular contractions of facial expression, the basic geometry of an individual face is essentially that of a rigid object that is clearly specified in a coordinate (i.e., quantitatively defined) space. In summary, we can define faces as "objects" made of a rigid, single, curved/smooth surface. In turn, this suggests that the brain's optimal representation for the above listed perceptual properties should be, respectively, metric, holistic, and smooth-surface-based. If the encoding of metric pattern information is required, then the underlying representation must be different from the bare registration of nonaccidental properties, over orientation and depth discontinuities, that imply figure–ground separations (Biederman & Kalocsai, 1997). Instead, it would seem to require as its underlying representation a more faithful replica of the original image, a "pictorial" model as it were (Ullman, 1996) or, using an old term, a template. Such a representation can be holistic ("integral," Shepard, 1964, or "nonanalytical," Garner, 1966), not decomposed into readily perceivable independent attributes (Tanaka & Farah, 1993). Alternatively, objects may be represented by parts' templates assembled into a volumetric multipart structure (cf. Moore & Cavanagh, 1998).

In order to capture those subtle differences that distinguish, for instance, the individual members of the same family, depth information specifying the curvature gradients would also seem necessary. Information about depth (either 2.5- or 3-D) could be derived principally from binocular stereo or structure-from-motion processes in ecological situations or, for the static displays of some visual arts and laboratory experiments, exclusively by occlusion, shading, and textural cues (cf. Cavanagh, 1987). Thus, if encoded as a holistic representation, the whole head may be represented as a "volume" (i.e., a 3-D enclosure or a CAD-like model), in other words, a surface plus material inside (cf. Tse, 1999). If such holistic representation is viewer-centered (Hill, Schyns, & Akamatsu, 1997; Troje & Bülthoff, 1996), then a human face may be represented by several depth views ("stereometric snapshots") differing in angle of perspective (cf. Sinha & Poggio, 1996). Hence, depth may constitute an explicit property of the fine-grained, subordinate level shape representation or it may greatly contribute to its organization (cf. Braje, Kersten, Tarr, & Troje, 1998; Hill et al., 1997; Hill & Bruce, 1996). Thus, an appealing model of object recognition may be one that incorporates both aspects of image-based and volumetric, possibly structural, descriptions (see Tarr & Bülthoff, 1998). Indeed, this would seem particularly necessary for those objects that include much smooth curvature deformations of a single surface.

PART 1: CASE REPORT

Clinical History

RP is a 47-year-old, right-handed, electrical engineer who at age 3 was diagnosed as having cerebral palsy. According to his own report, RP sustained head injury at age 7, when a trap-door fell on his head. Apparently, he became aware of his problem in face recognition only in his teenage

Table 1. Segmentation Data: Slices 4 to 57

	RP (vol cm³)	*Normals (vol cm³)*	*SD*	*Nl−RP*	*NI−RP as % Nl*
Right cerebral exterior	542.488	606.3	53.5	63.81	119.3
Left cerebral exterior	546.239	603.9	54.1	57.66	106.6
Right cerebral white matter	193.54	221.8	20.7	28.26	136.5
Left cerebral white matter	190.437	221.1	22.2	30.66	138.1
Right cerebral cortex	307.993	346.2	33	38.20	115.8
Left cerebral cortex	317.455	342.6	32.2	25.14	78.1
Right lateral ventricle	13.374				
Left lateral ventricle	10.329				
Right inferior ventricle	0.554				
Left inferior lateral ventricle	0.263				
Right lateral ventricle	13.928	8.1	3.1	−5.82	−188.0
Left lateral ventricle	10.592	9.8	4.6	−0.79	−17.2
Right cerebellum exterior	72.079	71.5	6.4	−0.57	−9.0
Left cerebellum exterior	73.952	71.9	6.1	−2.05	−33.6
Right cerebellum white matter	9.902				
Left cerebellum white matter	10.319				
Right cerebellum cortex	62.163				
Left cerebellum cortex	63.807				
Right thalamus proper	7.567				
Left thalamus proper	7.806				
Right ventral diencephalon	4.32				
Left ventral diencephalon	4.369				
Right diencephalon	11.887	10.2	0.9	−.68	−187.4
Left diencephalon	12.173	10.3	0.9	−1.87	−208.1
Right caudate	2.46				
Left caudate	2.884				
Right accumbens area	0.31				
Left accumbens area	0.308				
Right caudate	2.77	4.7	0.7	1.93	275.7
Left caudate	2.672	4.8	0.7	2.128	304.0
Right putamen	4.311	5.1	0.4	0.789	197.2
Left putamen	4.482	5	0.5	0.518	103.6
Right pallidum	1.349	1.9	0.3	0.551	183.7
Left pallidum	1.47	1.9	0.3	0.43	143.3
Third ventricle	2.238	1.3	0.5	−0.93	−187.6
Fourth ventricle	1.646	1.9	0.6	0.254	42.3
Brain stem	23.374	23.4	1.7	0.026	1.5
Left vessel	0.034				

(continued)

Table 1. *Continued*

	RP (vol cm^3)	*Normals (vol cm^3)*	*SD*	*Nl−RP*	*Nl−RP as % Nl*
Left hippocampus	4.604	4.9	0.7	0.296	42.3
Right hippocampus	4.284	5.1	0.7	0.816	116.6
Left amygdala	2.015	2.9	0.4	0.885	221.2
Right amygdala	2.139	2.6	0.4	0.461	115.3

Pix dim(x,y,sl) = 0.468750, 0.468750, 3.100000. Nl=Normal mean.

years. An initial unawareness of a visual problem is not unusual in developmental or congenital cases (consider cases of Daltonism). According to RP, he recognizes people mostly on the basis of their characteristic voice, memorizing clothing and other paraphernalia, and various contextual cues. Faces do not ''snap into focus'' once the identity of the person has been established. His deficit has caused him real problems in everyday social interactions. In constrained contexts, he can cope more successfully. On several occasions, he seemed to recognize the experimenter (BL), within the context of the laboratory setting, but never in chance meetings or in a novel setting. Always according to RP, people mistakenly describe him as uninterested in social relations and other people's emotions and states of mind. However, he does admit to having little interest in the imaginary social settings of novels, TV programs, or movies, and shows a clear preference for ''technical'' subjects like astronomy. A lack of interest for representations of role-playing may be easily explained a visual difficulty in keeping track of individual characters (cf. Cole & Perez-Cruet, 1964). Remarkably, a film that RP particularly enjoyed was ''Batman,'' in which all the main actors wear masks.

Brain Imaging

A (3-D) MRI sequence was conducted at the Massachusetts General Hospital (Charlestown, MA). The clinical interpretation of this scan was that there was no abnormality of brain shape or evidence of focal cerebral injury (i.e., indication of damage due to trauma or other focally acting process). Similarly, although the literature on other cases of developmental, congenital prosopagnosia is sparse, brain scans of these prosopagnosic subjects have also failed to show focal abnormalities (e.g., Ariel & Sadeh, 1996; Young & Ellis, 1989). However, the clinical analysis can be expected to be insensitive to volumetric abnormalities that arise consequent to bilateral, relatively diffuse, but low-level injury, occurring in utero and which might lead to incomplete or abnormal growth and organization of the neural substrate. In order to evaluate this possibility, data from RP were compared with those from a set of normal young adult controls of the same age range (N = 20; 10 males). Segmentation was performed with modern computerized technology developed at the Center for Morphometric Analysis. The comparisons are shown in Table 1, in terms of ''normal controls minus RP'' deviations in percentage of the standard deviations for the control subjects and Z score ratings of the patient's brain volumes with respect to the series of 20 adult normal subjects (see Makris, Meyer, Bates, Caviness, & Kennedy, 1999; Caviness, Makris, Meyer, & Kennedy, 1996; Filipek, Richelme, Kennedy, & Caviness, 1994). The analysis revealed a general pattern of prominent relative reduction in volumes of a limited set of structures in the right hemisphere (RH). Specifically, the patient tends to be at a volume that is less than a standard deviation from the normal mean for the hippocampus, neocortex, and pallidum of the RH while the right forebrain ventricular system in complementary fashion is relatively larger. Young and Ellis (1989) have previously reported dilatation of the ventricles as the only visible abnormality in the head CT scan of KD, a case that they have labeled as ''childhood prosopagnosia.'' Not many cases of ''developmental prosopagnosia'' have been described so far (e.g., McConachie, 1976), but it seems likely that this count may be an underestimation of the real number of people suffering from more or less severe degrees of the syndrome. Although the inability to recognize co-specifics is a severe handicap, it may be easily mislabeled or misinterpreted as some ''noncognitive'' type of problem (e.g., the patient's lack of social interest or attention, even some form of autism). Thus, we surmise that several of these cases may never reach the neurologist's office.

Neuropsychological and Neurophthalmological Examinations

A standard neuropsychological assessment conducted at the Spaulding Rehabilitation Hospital (Boston) showed nothing remarkable. Purely on the basis of these standard tests, RP's cognitive profile is entirely normal. RP's neurophthalmological profile, assessed at the Massachusetts General Hospital (Boston), was also normal. Interestingly, his color sensitivity (measured with the Farnsworth–Muensell 100-Hues test) is normal and RP does not show signs of achromatopsia.

Assessment of RP's Deficit with Face Stimuli

Identifying ''famous faces.'' RP was asked to examine photographs of various famous and popular figures (spanning from the 1920s to the 1990s; e.g., Elvis

Presley). RP claimed no sense of familiarity or identity (except for one picture, correctly named as "Jack Kennedy"). His guesses were all incorrect (even after semantic prompting, i.e., providing one piece of biographical information). Normal controls in their 50s can identify on average 41/56 pictures (or 54/56 after semantic prompts). Given a performance of 1/56 in both conditions, RP is clearly severely impaired at this task. When subsequently presented with the list of all the portrayed people's names and asked to provide some historical details (e.g., profession) about each of them, RP described correctly 34/56 individuals. The unnamed personalities were all from the domain of sports, cinema, and TV shows, which fall outside of RP's range of interests. In a separate session, the photos of the 34 correctly named individuals were presented in a forced-choice task, in which the correct name in a pair of names was to be matched to the photo. The foil name corresponded to some other personality in the same era and career field, sex, ethnicity (e.g., Mohammed Ali vs. Mike Tyson). RP claimed to be guessing and chose the correct name for 18/34 pictures (53%, chance level). This performance indicates a very severe form of prosopagnosia, since some prosopagnosic individuals (e.g., patient PV, Sergent & Poncet, 1990) can perform better than chance in a forced-choice two-alternative face–name matching task. RP's problem is not confined to establishing identity from photographs and other 2-D representations: He can provide anecdotes that exemplify everyday problems with the identification of persons to whom he has been extensively exposed.

Identifying sex and age from the face. RP confesses attending to hair as a way to collect clues on persons' identity. The use of such strategy can allow him to get by in a limited way in controlled social interactions (as it has been reported also for other prosopagnosics; Ariel & Sadeh, 1996; Bodamer, 1947/1990; Beyn & Knyazeva, 1962). RP's accuracy and efficiency in making estimates of the sex and age of a face were evaluated in a task in which hair-based cues were entirely absent (i.e., photos of bald-shaved female and male models). Whereas normal subjects could rather accurately attribute the correct sex to each model's portrait, for RP, all faces "looked invariably male" and, in fact, he misjudged all the female faces as male. A few control subjects also committed false assignments of sex but these were only occasional and equally frequent for each sex (three subjects made one "male-to-female" error, and two subjects made one "female-to-male" error). RP's latencies [mean response time (RT) = 6442 msec; *SD* = 3438] were clearly greater than the average of his controls (mean RT = 2114 msec; *SD* = 1015).

Regarding RP's ability to judge the age of the face of these bald models, estimates were taken in steps of 10 years (e.g., 20s) with a lower limit of 20 and an upper limit of 70 years. A simple regression analysis between RP's and the control subjects' estimates (after averaging) revealed a close positive relation; $R^2 = 71$; slope = 0.8, $t(83) = 14.1$, $p < .001$. Also, means and *SD*s of estimates were comparable (RP: mean age = 33.5, *SD* = 11.6; controls: mean age = 31.6, *SD* = 10.9) and there was no difference in the speed of such decisions (RP: mean RT = 3017 msec, *SD* = 1803; controls: mean RT = 1563 msec, *SD* = 1212). It can be concluded that RP can normally judge a person's age from the face.

Identifying facial expressions. RP complains of having difficulty in recognizing facial expressions. This was examined experimentally by use of a picture–name matching task. RP and controls first examined six gray-tone photos of six basic emotions, each labeled at the bottom of the page (i.e., anger, boredom, fear, joy, sorrow, and surprise). Subsequently, RP and controls viewed on the computer screen, for half a second, each of the pictures followed by a verbal label (spoken by the computer), either correctly or incorrectly naming the expression. At this presentation rate, control subjects can indicate flawlessly which labels are correct and their key presses are fast (mean RT = 611; *SD* = 125). Instead, RP's error rate was 38% (ranging from 50%—i.e., chance—for the expression of anger to 25% for those of boredom and sorrow) and his latencies were sensibly longer than those of the controls (mean RT = 4384 msec; *SD* = 2024).

The presence of problems in identifying faces, their sex, and in decoding expressions could occur because of chance involvement of independent perceptual mechanisms or, alternatively, it may reflect damage to the operation of a more primitive perceptual mechanism underlying those types of function. Whatever the cause of RP's deficit in decoding expressions, this appears to be a rather debilitating additional problem. Indeed, he blames a long personal history of failed relationships mostly on his inability to decode the emotional state of his partner.

PART 2: IDENTIFYING OBJECTS

In his daily life, RP can identify objects other than human faces. The preservation of this ability has been viewed as of great theoretical significance in studies of agnosia, since it suggests the existence of an independent, special, perceptual mechanism for human faces. However, faces and "other" objects do not simply differ by category, but there clearly exist several perceptual cues, features, geometric primitives, which can differentially contribute to their pattern representations. One possibility that cannot be overlooked is that a prosopagnosic may have a "subclinical" impairment (i.e., an impairment that does not pose a problem for the individual in his everyday life setting) in object recognition. Such impairment may escape detection by most clinical and experimental tasks and rarely or never become a formal complaint of either the patient or the immediate social environment. Nevertheless, from a theoretical viewpoint, the presence of even a subtle impairment in object recognition in the presence of prosopagnosia is of great relevance. Moreover, several accounts of the syndrome of prosopagnosia posit, as the locus of impairment, a pattern analysis mechanism that is shared in the encoding of faces and objects, although it is less necessary for the latter kind of patterns than the former (cf. Farah, 1990, 1995). Within such perspectives, more or less subtle impairments affecting different classes of objects of perception should always be observable, given that researchers take the effort to develop valid and sensitive enough measures.

Experiment 1: Identifying Objects Seen in Difficult Perspectives (Noncanonical Views)

Every object would seem to be identified optimally from a particular range of perspectives, whereas it can take more scrutiny and it can even be confused with other objects when it is seen from other specific perspectives. The optimal perspective for object identification has often been referred to as the ''canonical'' view of such object (Palmer, Rosch, & Chase, 1981). Because informational content may be stable, rich, and varied in the canonical view, it is likely that recognition from this perspective will be more resistant to a deficit in the perceptual encoding mechanism (cf. Warrington & Taylor, 1973, 1978; Newcombe & Russell, 1969). Indeed, RP was able to identify all of the Snodgrass and Vanderwart's (1980) pictures, each presented at only 30 msec, and at a speed no different from that of matched controls (these patterns are made exclusively of edges and represent objects as seen in rather typical, conventional, or canonical views). RP and the control subjects were also asked to name gray-tone depictions of various kinds of objects seen, for only 30 msec, from odd or noncanonical points of view (e.g., a desk phone seen from the bottom). This is a challenging object identification task, since in these unusual perspectives, the object's characteristic outline, features, and principal body axis, are not clearly visible.

Results and Conclusions

RP named correctly all the pictures and so did the control subjects. Additionally, RP's and the controls' RTs showed no reliable difference (RP: mean RT = 2632 msec, *SD* = 794; controls: mean RT = 1871 msec, *SD* = 673). Clearly, despite the data-limited conditions of these views, there was no detectable difficulty for RP in providing entry-level names. If surface information is more relevant for subordinate-level recognition, whereas basic-level identification can be accomplished efficiently from encoding edge information and RP's deficit did affect the former but not the latter, then he would be expected to be able to identify even difficult noncanonical views of objects, as long as the tasks require a level of identification that is either basic or superordinate. Edge-based encoding has also the advantage of providing some degree of orientation-invariance.

Experiment 2: Identifying Objects from Two-Tone Pictures (''Mooney'' Stimuli)

Two-tone images lack the shading, hue, and texture information of the corresponding objects, and they present only black-and-white regions corresponding to areas of cast shadows. Yet the objects in these images appear to normal subjects as fully volumetric and distinguishable from their shadows. Although shadows provide information about surface shape, they also introduce spurious edges that must be discounted prior to recognition. Normally, shadows improve surface or volumetric encoding (Tarr, Kersten, & Bülthoff, 1998) but, at the same time, they may hinder edge-based object description (Braje et al., 1998). Importantly, two-tone images may particularly disrupt the shape-from-shading process for the encoding of curved surface information (cf. Johnston & Passmore, 1994), since cast shadows would make a curved surface uniformly dark (instead of having a shading gradient; cf. Braje et al., 1998). An additional property of two-tone images is that their correct interpretation strongly depends on previously stored representations in memory or a top-down process (Cavanagh, 1991), since two-tone images of novel objects do not lend themselves to volumetric interpretations (Moore & Cavanagh, 1998). In clinical neuropsychology, two-tone images of faces are often used as a diagnostic tool (Mooney, 1956). Many prosopagnosics (if not all) seem to have particular trouble with these binary-tone images (e.g., Levine & Calvanio, 1989).

Since even the normal subjects' perception of such images is not mediated by bottom-up extraction of geometrical features, a perceptual deficit for the recognition of two-tone images of faces and not for objects would reveal that the underlying geometry of faces cannot be stored by RP, whereas the geometric features of other objects can. Two-tone images of faces and of nonface objects, i.e., animals, body parts, and artifacts (see Figure 1) were presented individually on the computer screen.

In the face task, subjects were asked to judge the sex and the age of each face. RP claimed to be able to see a face from these images in only 31% of the figures, but his judgments of the face's sex or age in such trials was entirely at chance (50% and 55% correct, respectively). It is doubtful that even in those trials in which RP claimed to be able to see a face was he correctly able to identify the true face shape in the image. When questioned about the orientation of the face and asked to point to particular facial parts (e.g., mouth, nose), RP indicated mainly profile view interpretations (instead of the correct $\frac{3}{4}$ orientations). In tracing with his finger, he showed a marked tendency to indicate a continuous edge as part of the overall contour or silhouette of a face, ignoring the fact that in these pictures, salient edges do not corre-

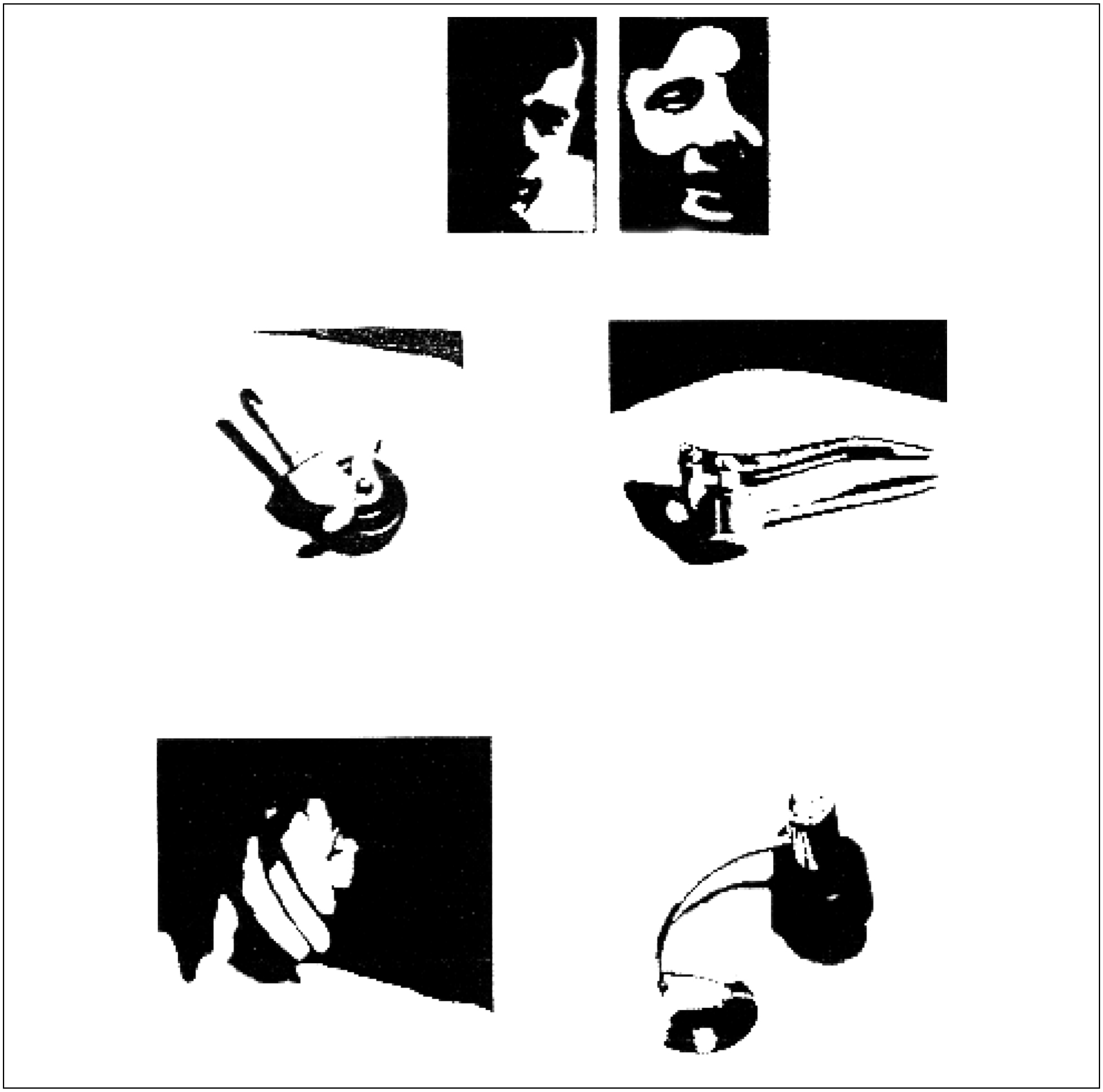


Figure 1. Experiment 1. Examples of "Mooney" faces and objects.

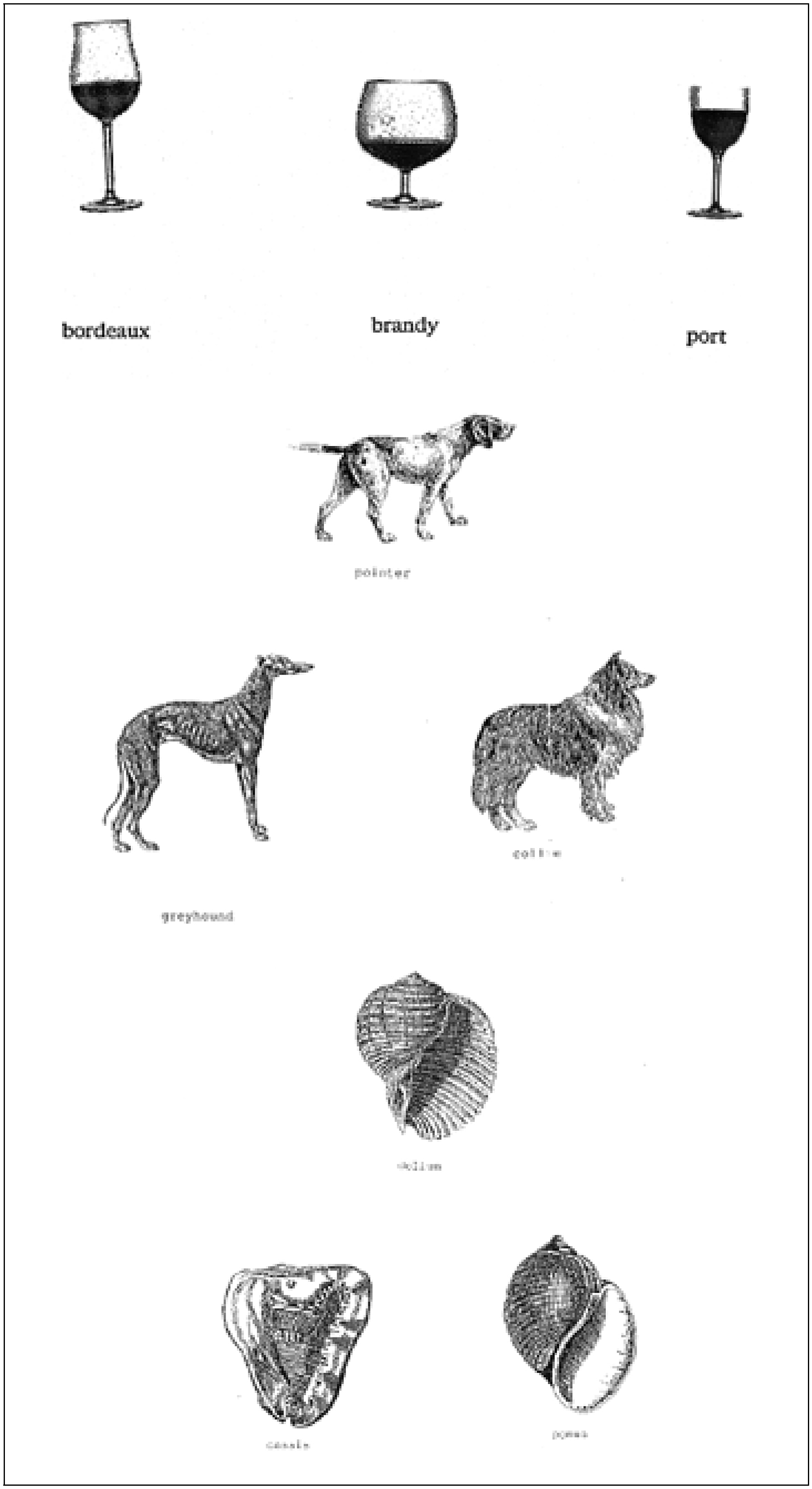
spond to real boundaries between parts. RP's inability to perceive the shape of faces from shading was in stark contrast with his ability to identify binary images of animals and artifacts. For this material, RP recognized all the objects, even infrequent/odd ones that were not solved by two of the control subjects (e.g., a garlic press, a caster). Moreover, RP responded always within 0.5 to 3 sec from presentation, whereas for some of the normal subjects, latencies longer than 3 sec were observed.

In conclusion, RP's ability to recover shape-from-shadow is intact for basic-level recognition of objects, but completely deficient for faces. RP's inability to judge the age of a face in a two-tone image is in sharp contrast with his ability to judge its age from gray-tone images. We conclude that, because RP showed a clearly marked dissociation in what is likely to be an entirely top-down perceptual task, this indicates a severe lack in RP's pattern memory of the basic geometric representation of the human face but not of other objects.

Experiment 3: Identifying Objects at Subordinate Versus Basic Levels

As we saw, RP can identify drawings of objects even when seen in very data-limited conditions (e.g., tachistoscopic presentations, unusual perspectives, two-tone

Figure 2. Experiment 3. Objects within categories. From top to bottom: drinking glasses, dogs, and seashells.



images). It would be tempting to conclude that recognition of objects has been entirely spared. However, there are reasons to believe that this would be a premature conclusion. In the previous tests, although stimuli were complex, the required level of identification was simple, indeed what psychologists and philosophers typically refer to as the "basic" level (cf. Smith & Medin, 1981). Subordinate identification requires a more precise mapping between a pattern and a specific physical object than basic-level recognition; and, as it has often been pointed out (e.g., Gauthier et al., 1997, 1999; Levine & Calvanio, 1989; Damasio, Damasio, & Van Hoesen, 1982), face identification requires subordinate-level category distinctions.

If surface information is more relevant for subordinate-level recognition (Biederman & Ju, 1988), we reasoned then that RP may show abnormalities in identifying objects at this level of categorization. Therefore, the following experiment required subordinate-level identification of various classes of objects all containing, in variable degrees, curved surface-based information, i.e., animals' bodies, artifacts (like shoes, chairs, drinking glasses, and automobiles), and human faces (see Figure 2). Edges, either straight or curved, and textural plus shading information are clearly depicted in the stimuli we used, therefore the object's surface geometry can be inferred from such properties. Stimuli were presented tachistoscopically, and at the offset of each visual stimulus, a name was heard from the computer's speaker, which matched either correctly or incorrectly the previously seen object. Importantly, each name could be correct at either the basic level (e.g., see a picture of a poodle and hear "dog") or at the subordinate level (see the poodle and hear "poodle"). The photos of faces were not cropped and included hair; for the basic level label we used sex (male vs. female) and common proper names (e.g., Anne, Frank) as the subordinate labels.

Results

The percent error rate and RTs to correct trials were initially averaged for each kind (i.e., animals, artifacts, or persons), ignoring individual categories (e.g., cows or dogs). Data from the control subjects and RP were analyzed in two separate repeated-measures analyses of variance, with label (basic/subordinate) as the within-subject factor. As shown in Table 2, controls committed fewer errors in matching faces (mean % error = 10.5; *SD* = 3.3) to basic labels (i.e., male/female) than to subordinate labels or proper names (mean % error = 14.3; *SD* = 7.8). Controls were also overall faster (mean RT = 1133; *SD* = 113) in matching basic labels than subordinate labels (i.e., proper names; mean RT = 1345; *SD* = 162); $F(1,9) = 49.4$, $p < .0001$. Also, RP found it easier, $F(1,92) = 10$, $p < .002$, to assign basic labels to faces than subordinate ones (basic: mean % error = 34, *SD* = 33; subordinate: mean % error = 15.3, *SD* = 24) and, consistently, his performance was faster with basic (mean RT = 2243; *SD* = 952) than subordinate names (mean RT = 4427; *SD* = 2012), $F(1,92) = 10$, $p < .002$. As expected, RP was both less accurate and slower than the controls in matching proper names to the faces. Both measures fell several standard deviations beyond the controls' means (see Table 2). He was, however, within normal limits of accuracy for basic (sex) labels but still slower than the control subjects for such decisions.

Table 2. Experiment 3: Means (and *SD*s) of Errors and RTs of Control Subjects and Mean Performance of RP for Each Kind (Human Faces, Artifacts, Animals) and for Each Label (Basic, Subordinate)

	Control Subjects		*RP*	
	% error	*RTs*	*% error*	*RTs*
Human faces				
Basic	10 (3)	1133 (112)	16	2225
Subordinate	12 (4)	1345 (166)	34	4428
Artifacts				
Basic	5 (3)	1135 (98)	6	1542
Subordinate	10 (3)	1225 (187)	15	2885
Animals				
Basic	7 (3)	1085 (116)	8	1652
Subordinate	16 (4)	1256 (123)	22	3399

When matching artifacts to category names (i.e., cars, chairs, glasses, and shoes), RP's mean percent errors did not exceed 2 *SD*s of the error rates of the control subjects (as shown in Table 2, this is true for every condition). However, several differences appeared in terms of performance efficiency. First of all, RP was 7 *SD*s slower (mean RT = 2121; *SD* = 474) in making correct judgments than the control subjects (mean RT = 1130; *SD* = 175). Additionally, RP was 4 *SD*s slower in matching basic labels than the controls (RP: mean RT = 1542, *SD* = 79; controls: mean RT = 1135, *SD* = 98). He was even more impaired for matches to subordinate labels (RP: mean RT = 2885, *SD* = 299; controls: mean RT = 1225, *SD* = 187) and his mean RT differed more than 8 *SD*s then the controls'.

Regarding matching animal shapes to names, it again appeared that RP and the control subjects did not differ in their performance accuracy (see Table 2), since RP's error rate was always within 2 *SD*s from the mean of the controls' performance. But once again, RP was 10.5 *SD*s slower (mean RT = 2525; *SD* = 248) in making correct judgments than his controls (mean RT = 1170; *SD* = 129). Moreover, RP was 17 *SD*s slower in judging

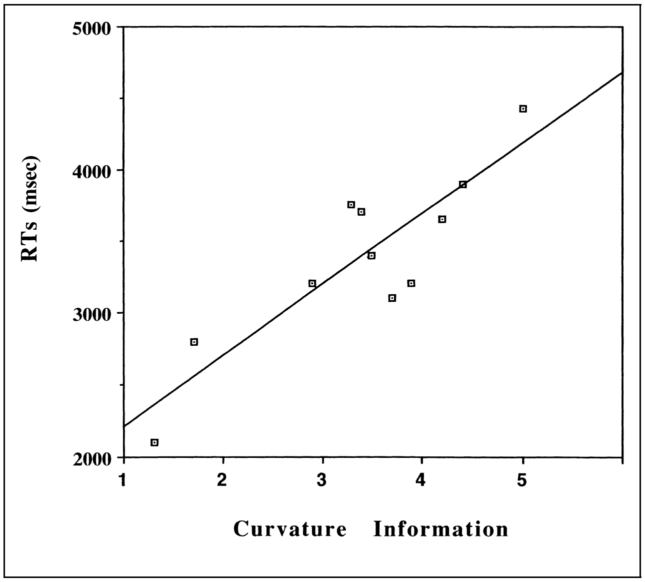


Figure 3. Experiment 3. Simple regression of curvature information in each class and mean RTs of RP to subordinates labels.

matches with subordinate labels than the controls (RP: mean RT = 3399, *SD* = 392; controls: mean RT = 1256, *SD* = 123) and he was 4.8 *SD*s slower than the controls when matching basic labels (RP: mean RT = 1652, *SD* = 68; controls: mean RT = 1085, *SD* = 116).

These findings suggest that RP's visual system may be deprived of the perceptual information that normally supports the representation of exemplar shapes. Possibly, the recovering of curved surface properties may be inadequate and consequently, more "perceptual sampling" (reflected in longer RTs) of these or other relevant shape properties (e.g., texture and edge-based information) would have to take place in the patient's case than in the normal subjects'. In order to evaluate more closely this hypothesis, we assessed whether more curved information present in the stimuli correlated with more time taken by RP in matching their names correctly. The relative amount of curved information in each drawing was estimated on a five-step scale by independent judges, and these scores were then averaged within each stimulus class (e.g., chairs, dogs). Although there exist formal methods for quantifying the amount of curvature of an object, we took advantage of the human eye's hyperacuity for spatial discriminations of curvature to order each kind. When the obtained "curvature scores" were used as a variable in a simple regression analyses of RP's RTs for subordinate matching in each class, we found the expected positive relation between the two variables (slope = 493 msec; $r = .88$), $t(10) = 5.6$, $p < .004$ (Figure 3).

Conclusions

RP's perception is clearly not normal for several classes of objects. Interestingly, the accuracy data, while confirming RP's abnormal performance with human face stimuli, failed to suggest any other recognition deficit. If we had limited our analysis to accuracy, we could have concluded that the patient showed a highly circumscribed problem with human faces, supporting the existence of a "pure" form of prosopagnosia. However, the RT data clearly demonstrate how mistaken such a conclusion would have been (see also Gauthier et al., 1999, for a similar finding). A likely reason for the disparity between accuracy and efficiency measures is that it may be always sufficient to distinguish and recognize natural objects or artifacts on the basis of purely edge-based information. When sufficient constraints are available, identification may be accurate but slowed by the lack of other additional constraints. In some cases, even a single visual feature (e.g., elongation of an edge; cf. Arguin, Bub, & Dudek, 1996) may be sufficient for establishing a difference. A look at Figure 2, for example, suggests that the identity of different wineglasses could be established purely on the basis of the elongation of the stem. Yet, curvature information adds further constraint to their identity, since each wineglass could also be distinguishing in terms of degree of curvature of the cup. Moreover, curvature information would appear to be even more relevant for distinguishing species of animals, although in this case, texture or high-contrast markings can certainly add additional constraints (making these classes less perceptually homogenous than faces; cf. Dixon, Bub, & Arguin, 1998). For artifacts, the degree to which their shapes may be characterized by curvature information can be variable. In the present case, according to our visual estimates of relative amount of curvature to straight-edges information, it was maximal for shoes and glasses, average for cars, and minimal for chairs. Importantly, these estimates did correlate with increasing latencies in RP's subordinate-level identification of each class.

It is interesting to note that in studies showing an association between face-processing deficit and impairment for subordinate levels of object identification, the problematic classes are invariably of objects with curved features: animals, cars, or "greebles" (see Gauthier et al., 1999). This fact is suggestive of a problem with a common mechanism shared by these classes. In contrast to studies revealing such associations, a few studies have argued for a dissociation of prosopagnosia from the spared recognition of "unique" objects. Specifically, in a study by De Renzi (1986), prosopagnosics could identify personal objects (e.g., the patient's wallet or watch among others'). Unfortunately, this evidence is rather inconclusive when examined to the light of a possible deficit in processing surface-based information. Items of practical use could be learned, prior to test, to be identified on the basis of a few salient features (probably edge-based) as well as color and texture; therefore, without necessarily implying the use of surface information for their recognition. Additionally, many personal objects do not contain much curved-surface geometry (e.g., a wallet, a necktie, and even several kinds of eyeglasses). Moreover, several object classes (e.g., chairs and eyeglasses; see Farah, 1995) that have been used in comparing the prosopagnosics' ability to match nonface classes at the subordinate level seem also to contain little curved surface. Finally, McNeil and Warrington (1991, 1993) showed that two ''prosopagnosic farmers'' could still identify the faces of their own animals. One patient could recognize his cows and another, his sheep. Yet, it is not clear whether these animals could not also be distinguished on the basis of edge-based salient features and clearly unique textural elements (e.g., patches of fur, high-contrast facial markings; cf. Bruyer et al., 1983). Hence, it seems premature to conclude from these patients' performance that their perception for ''nonhuman face'' objects is completely normal, especially if such a conclusion is solely based on measures of accuracy.

PART 3: PERCEPTION OF GEOMETRIC PRIMITIVES

Curved lines play an important role in object recognition (Attneave, 1954), and human spatial discrimination of curvature has been placed among the hyperacuities of our visual system (i.e., greater resolution than the physical spacing of cones or receptive fields of retinal cells). According to Riggs (1973, 1974), the detection of curvature is a primary function of cortical neurons sensitive to end stopping and stimulus length. At least one case of prosopagnosia, GA, has been described so far (Kosslyn, Hamilton, & Bernstein, 1995) as someone who showed a peculiar inability to discriminate curved lines. Consistently, these authors interpreted this patient's prosopagnosia as a by-product of a (speculative) loss of a population of ''end-stopped'' neurons that are relevant in encoding curvature information.

Experiment 4: Discrimination of Straight Lines Versus Curved Lines

From the evidence collected so far, it seems likely that RP suffers from a similar type of perceptual encoding deficit as GA's. Therefore, RP's ability to encode curved versus straight features was evaluated with the same 2-D, gray-tone shapes (see Figure 4) used by Kosslyn et al. (1995). In one type of task, subjects decide whether a cross appears either on or off a shape. The lines constituting the cross and the shapes' perimeters are either made exclusively of straight lines or are all curved. In another type of task, pairs of displays containing simple shapes are presented side to side and the subjects are requested to decide whether the two displays are identical or not. Again, shapes are either all made of straight lines (i.e., rectangles) or of a curved perimeter (i.e., ovals).

Clearly, RP was not impaired in these tasks (see Table 3). Possibly, these tasks tap a very low-level problem with curvature information, since they require judging curvature in elementary 2-D (flat) displays, which lack depth or volumetric interpretations. Faces, instead, are 3-D objects (as well as animals or artifacts are) and are perceived as volumetric even when seen as 2-D representations. Therefore, the next and final experiment assessed whether RP is impaired in discriminating poly-

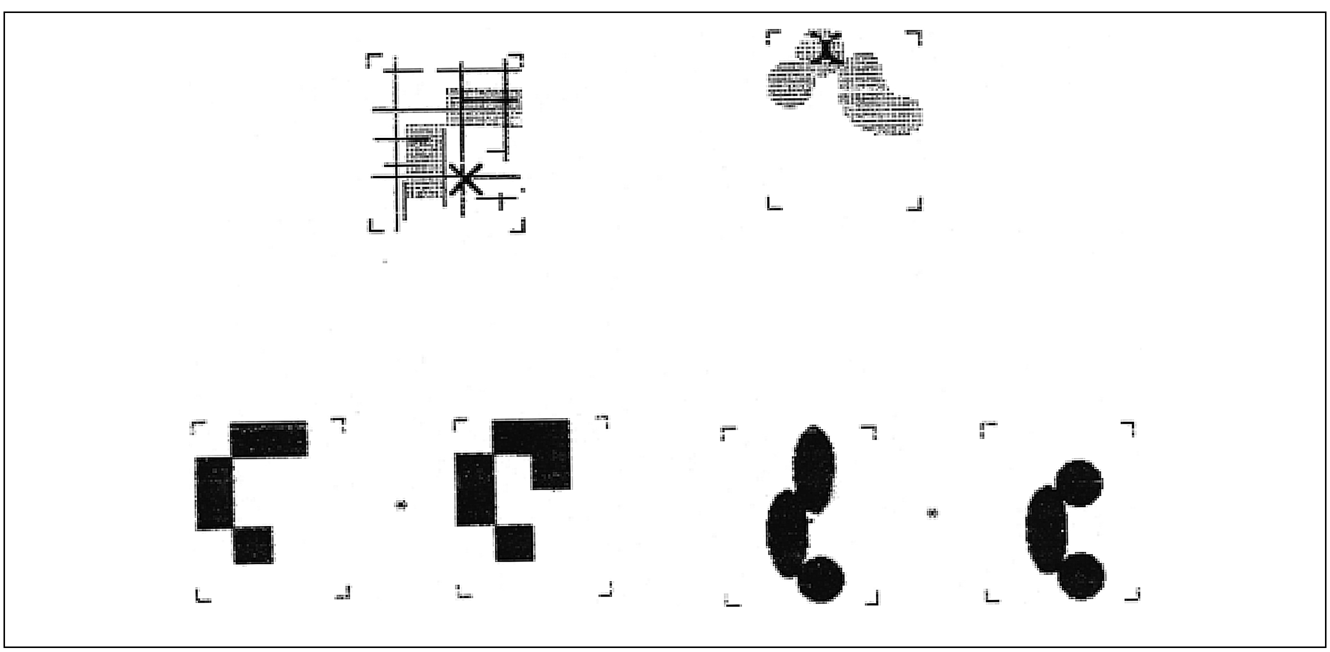


Figure 4. Experiment 4. Straight versus curved lines tasks. Top row: on/off task. Bottom row: same/different task.

Table 3. Experiment 4: Means (and *SD*s) of Errors and RTs of Control Subjects and Mean Performance of RP in Each Subtest (On/Off, Same/Different) for Each Feature Type (Straight/Curved Lines)

	Control Subjects		*RP*	
Tests	*% error*	*RTs*	*% error*	*RTs*
On/off, straight	4 (3)	1094 (44)	8	1176
On/off, curved	1 (2)	901 (65)	2	1094
Same/different, straight	2 (4)	1264 (65)	3	1170
Same/different, curved	4 (3)	1298 (77)	5	1362

hedrons (i.e., volumes whose surfaces are bounded by straight edges) as opposed to volumes made exclusively of a curved surface.

Experiment 5: Matching Depth Rotations of Cubes Versus Depth Rotations of Curved Single Surfaces (''Amoebae'') and Faces

A few investigators have explored cognitive performance for rotations of faces, hands, and some artifacts; but curved stimuli consisting of just geometric primitives and devoid of symbolic meaning (i.e., the curved analog to the classic ''Shepard–Metzler'' cubes task) have been less used. One of such exceptions is a study by Hill and Bruce (1996) on same/different judgments of rotations of curvilinear nonsymbolic volumes, nicknamed ''amoebae'' (see Figure 5). Interestingly, Hill and Bruce found that lighting from above (vs. from below) facilitated matching of both normally upright faces and of the amoebae, a finding that would not be expected if face processing were based exclusively on edge-based representations. Instead, it suggests that the 3-D curved surface of these volumes is encoded and used in the matching. We used the same stimuli devised by Hill and Bruce, where each different amoebae could be seen at two different angular positions (corresponding to a 45° rotation) around the vertical axis.

The ''Shepard–Metzler'' task (Shepard & Metzler, 1971) requires to mentally image a 3-D polyhedral structure as it rotates in mental space (along one or more of the three Cartesian axes). As in the classic study, we presented pairs of cubes to subjects who were asked to judge whether each pair represented two different objects or the same object at a different orientation. A cube's assembly could appear in one of three perspectives, differing in steps of 40°. Similarly, in the face rotations task, two faces appeared side by side on the screen while the subject judged whether the two pictures represented the same individual or not. There were four different angles of rotation in steps of 30°. Hair was not visible in these pictures, in order to exclude the use of textural properties extraneous to surface information.

Results

All subjects showed, with the cubes task, the expected increase of both errors and RTs with increasing angle of disparity between views of the same shape. Control subjects' average error rates were 15% (*SD* = 21) for 40° disparities and 27% (*SD* = 29) for 80°. In trials where the volumes were different, the average error rates were 11% (*SD* = 12). Similarly, their average RTs were 1768 msec (*SD* = 639) for 40° disparities and 2378 msec (*SD* = 995) for the 80° condition; and 3108 msec (*SD* = 1711) for ''different'' trials. Both RP's error rates and RTs in the cubes task were within normal performance. His average error rate in ''same'' trials was 11% for 40° disparities and 25% for 80°, whereas in ''different'' trials his error rate was 9%. In ''same'' trials, RP's RTs were 1548 msec for 40° disparities and 2662 msec for the 80° condition; in ''different'' trials, the mean RT was equal to 4004 msec.

Also in the face rotation task, subjects showed the classic relationship between performance speed and spatial displacement and RTs increased with increasing angles of disparity between the two faces. However, whereas the control subjects' increase in RT was, on average, about 90 msec for every 30° of disparity, RP showed an increase of about 10 sec (i.e., mean RT = 11.5 sec at 0° disparity, 21 mean RT = 25 sec at 30° disparity, mean RT = 30 sec at 60° disparity, and mean RT = 48 sec at 90° disparity). Additionally, whereas the controls made no errors, RP showed also an increase in error rate with increasing angles of disparity. RP committed no errors only in trials when there were zero degrees of disparity between two angular rotations of the face; however, for every 30° disparity between the angular rotations of faces, there was an increasing cost in his error rate of about 10% (i.e., 9.3% error at 30° disparity, 21.1% error at 60° disparity and 30.8% error at 90° disparity). Thus, even slight changes of perspective caused an abnormal drop in either measure of RP's performance. Additionally, despite the high number of repetitions of each model's face and their small number (three men and three women), when RP was asked how many different persons appeared on the screen, he guessed about six men and six women. The RT data should be convincing that even when RP's performance is accurate, this is the result of an extremely slow and painstaking analysis of the stimuli.[1]

In contrast with the performance in the mental rotation of cubes, but similarly to his performance with rotated faces, RP showed an abnormal performance with the abstract curved shapes or amoebae. Control subjects' average error rates when the same shape was presented were 1% (*SD* = 1) for 0° disparity and 22% (*SD* = 9) for 45°. Their average error rate for different matches of these shapes was 13% (*SD* = 14). Average RTs in these

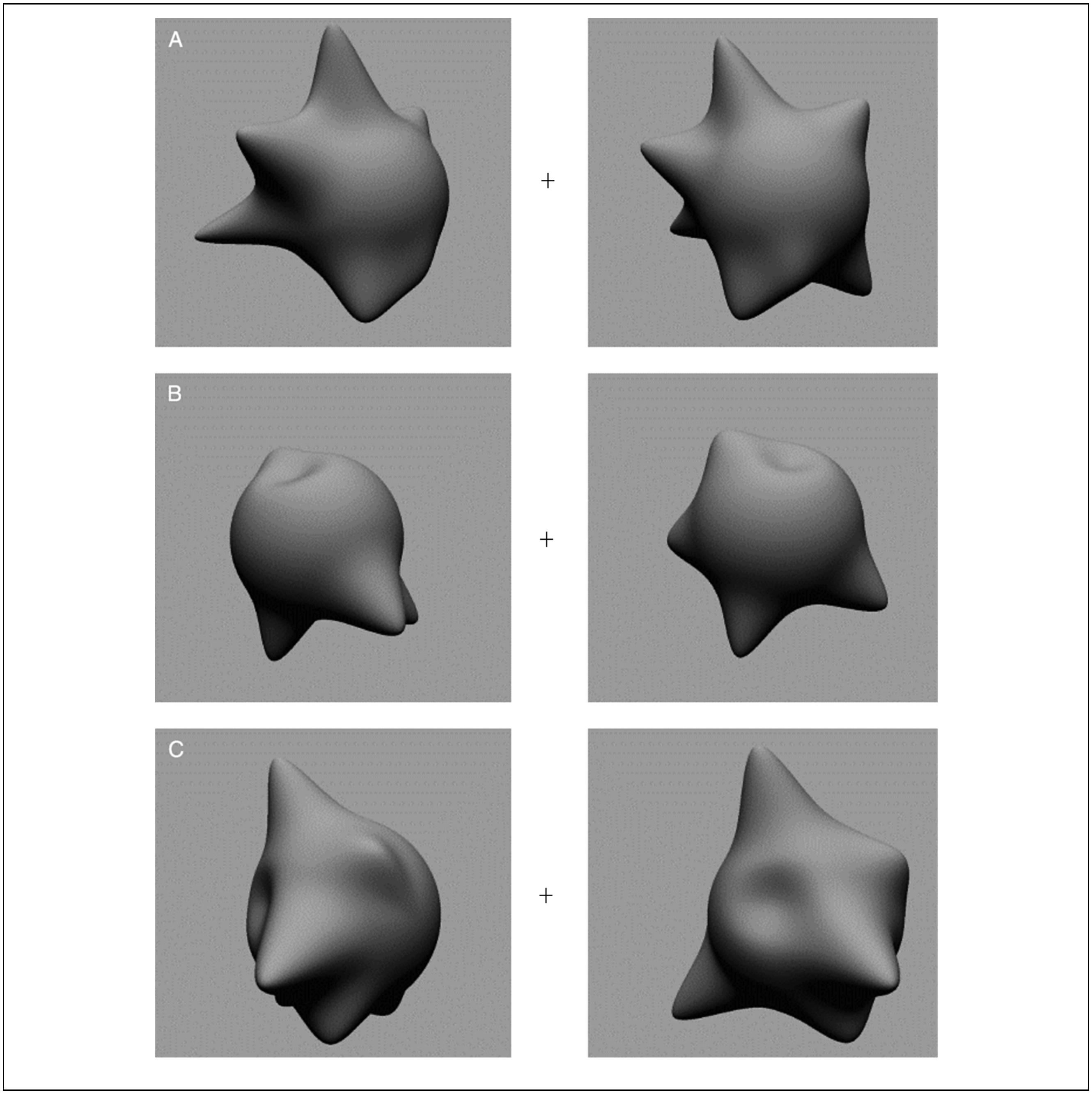


Figure 5. Experiment 5. (A) Amoeba, Example 1. (B) Amoeba, Example 2. (C) Amoeba, Example 3.

''same'' trials were 1093 msec (*SD* = 476) for a 0° disparity and 1561 msec (*SD* = 633) for the 45° condition. For ''different'' trials, the average RT was 1379 msec (*SD* = 569). In contrast, in ''same'' trials RP showed an error rate of 18% for the 0° disparity and 52% for the 45°. In ''different'' trials, RP showed an error rate of 44%.

Discussion

RP is unable to match two different perspectives of a same smooth curved shape. His performance is better, although impaired, when seeing the same shape in the same perspective, possibly because the shape's overall outline can be matched by ''juxtaposing'' templates. Importantly, RP is impaired for perceptual judgments of curved volumes (amoebae) but not of ones made of straight angles and edges (cubes). The impairment in the curved-surfaces task is even more striking when we consider that normal subjects have more difficulty with the cubes than with the amoebae or faces. Moreover, an impairment in discriminating curved volumes/surfaces in depth, but not curved features for 2-D patterns, suggests that RP's problem in face recognition is specifically related to a visual deficit in specifying the 3-D representation of a smooth surface.

Interestingly, when specifically questioned, RP asserted that the amoebae looked like ''balls'' and could not be mistaken for faces. This association between impairments with faces and stimuli, which share basic geometric properties with faces (but are not confused with them), speaks strongly against an explanation of RP's deficit as the damage to a face-specific module (e.g., Moscovitch et al., 1997). According to this account, the human brain possesses a module that rapidly identifies face schemata in the input and then codes (independently from a general-purpose object recognizer) a holistic, orientation-specific, representation of internal, second-order relational features of the face. Another current account, somewhat related to the face-specific module hypothesis, is that prosopagnosia is caused by damage to a holistic processor used both in object and face recognition, though more in the latter than in the former (Farah, 1990). According to this view, amoebae could be objects that, like faces, are primarily processed as wholes and that are not reflexively decomposed into parts (although such decomposition is not impossible, according to procedures based on concavities, see Hoffman and Richards, 1984). Instead, the Shepard–Metzler cubes may not be handled holistically (Just & Carpenter, 1976), but through transformation-and-comparisons processes in discrete steps over individual parts of the figures. Nevertheless, an account of RP's deficit as the reflection of an undeveloped holistic shape recognizer would still beg the question of why a holistic encoding would be preferred for some objects to one based on parts-based structural descriptions. In our view, the answer likely lies in: (a) the requirement for great spatial detail (lost in the abstract format of such structural descriptions) for obtaining an uniquely unique match of a face to an individual and (b) the inherent computational complexity of curved surfaces, which require a coordinate matrix or lattice that preserves with high fidelity the original spatial structure, thus approximating the image itself, constituting a template.

GENERAL DISCUSSION

The investigation of this single case, RP, provides a new set of findings and perspectives on the nature of the neurological syndrome of prosopagnosia. RP can solve perceptual problems involving nonface objects, while his personal history testifies to a severe problem in identifying faces, as well as facial expressions. If we had observed RP's performance merely in terms of accuracy, we could have concluded that ''object'' recognition was entirely spared for this patient. The only exception to such a conclusion would have been the matching of amoebae-like stimuli (i.e., depictions of volumes made of a single smooth surface), but considering that the latter task is not part of the standard cognitive tasks used in the assessment or study of prosopagnosia, RP's performance may have posed a very strong case for the existence of a ''pure'' form of prosopagnosia (i.e., a visual recognition deficit entirely specific to human faces). Moreover, since we took into account the speed or efficiency of performance for most tasks, it became clear that the patient's cognitive performance was outside the normal limits. Thus, one preliminary conclusion from this study is purely methodological: Ignoring RT data in the patient's performance would have led to inappropriate conclusions (see also Gauthier et al., 1999). The present case reinforces the suspicion that there is no support to the hypothesis that prosopagnosia fully dissociates from object agnosia. However, it seems fair to say that, at least for RP, the abnormal performance with nonface objects can be a rather minor problem, compared to that with faces. From the purely clinical perspective, his reduced efficiency (RT) in object naming clearly occurred at a level of severity that does not compromise the patient's functioning in everyday life's activities.

From a theoretical perspective, the most interesting aspects of this study of RP's abnormal performance was that the clearest losses of cognitive efficiency occurred for (1) in the perceptual matching of objects containing curved-surface information and (2) the identification of objects and artifacts at subordinate level of semantic categorization. One inference from these data would be that information about curvature of surfaces and volumes may provide powerful additional constraints to identification that are absent in edge-based structural descriptions. Indeed, perceptual information about curved surface may be most useful at the most subordinate levels of identifications (cf. Biederman & Kalocsai, 1997). RP's perceptual deficit appears grounded on specific high-order levels of shape structure, where curved surfaces and, possibly, volumes are described. A generic deficit in encoding simple curved features (e.g., curved contours or edges) can be ruled out. In conclusion, we propose that prosopagnosia can be the result of a perceptually based impairment in the representation of smooth surface. Interestingly, Case S. of Bodamer (1947), the very first case ever described under the label of prosopagnosia, reported that faces appeared to him as: ''Strangely flat, white with emphatic dark eyes, as if made from a flat surface, like white, oval plates, all alike.'' It is possible that prosopagnosia as a problem in representing curved volumes may have been the underlying cause (or at least a contributing factor) in several of the ''classic'' cases of this syndrome.

But if RP's behavior (and possibly of other patients) is the result of a perceptual impairment of smooth curved surface, why doesn't he show a similar problem for many classes of nonface objects? After all, in the physical world of objects we live in, human faces are not the only smooth and curved objects. The answer to this dilemma could lie in the fact that a visual system deprived of curved surface information can have elementary, but sufficient, perceptual skills in describing edges and contour (or other types of surface information), and this may suffice for the identification of many common natural objects. The observed association of deficit between the perception of faces and of artificial stimuli that share the primitive geometric property of curved smoothness strongly suggests that, for at least RP's case, an interpretation of prosopagnosia as the damage to a "face-specific module" seems a rather insufficient, possibly misleading, account.[2] The perceptual mechanism used to represent single smooth surfaces may have emerged as a consequence of the need to recognize our co-specifics. In this sense, by a sort of evolutionary bootstrapping, our brain may have developed the computational neural substrate for curved volume description. Alternatively, it may as well be that the perception of faces is merely supported by brain areas that carry out the necessary computations for complex curved-surface information, which evolved independently (and prior to kin-selection pressures) to provide useful constraints to visual perception.

Finally, about our neuroanatomical findings, there was the presence of abnormality in the volume comparisons of several substrates of RP's brain, particularly within the RH. Developmental cerebral abnormalities may not be visible at the gross level of topographic neuroanatomy, but modern computerized techniques can identify subtle volumetric differences associated with changes in brain structure. Indeed, the segmentation analysis revealed smaller volumes in several regions of the RH with complementary enlargement of the right forebrain ventricular system. This set of findings is consistent with the hypothesis that, in RP's case, injury occurred at a late prenatal or perinatal stage of fetal life and impeded the normal development of specific areas in the RH. Studies of patients with CVAs or TBI (e.g., Takahashi, Kawamura, Hirayama, Shiota, & Isono, 1995; De Renzi, Perani, Carlesimo, Silveri, & Fazio, 1994; De Renzi, Scotti, & Spinnler, 1969; Meadows, 1974) and PET, fMRI, or EPR studies of normal subjects (e.g., Kanwisher, McDermott, & Chun, 1997; McCarthy et al., 1997; Sergent, Ohta, & MacDonald, 1992) have established a clear connection between areas of the RH and facial perception. The left hemisphere may play mainly a supportive role to face identification (see Laeng & Rouw, in press). Moreover, a few studies have shown that depth perception is more dependent on areas of the RH than the left (e.g., Danta, Hilton, & O'Boyle, 1978; Oxbury, Campbell, & Oxbury, 1974; Benton & Hecaen, 1970; Carmon & Bechtold, 1969). Until now, there have been no reports attempting to relate a developmental perceptual disorder to the underlying brain volumetric aspects. Thus, we have no reference for prediction of how much tissue reduction is needed to reduce functional capacity. If the injury occurred in utero or during the perinatal period, it may tend to leave no trace in the form of an obvious focal wedge or infarction. Therefore, a minor but systematic difference of volume of brain tissue and ventricles may turn out to be of great significance. Higher resolution parcellations than the one described here, combined with tensor analyses of fiber tract anatomy, may be capable of revealing more region or structure-specific anatomic defects (e.g., posteriorly in the parietal or medial temporal regions of the RH), but such reduction may not be greater than 2 *SD*s. Extreme reduction of brain tissue in fact may not be needed (and should such a dramatic change have occurred the deficit might have been greatly more severe and cognitively devastating). These are issues that haunt the pioneering nature of this case analysis, where volumetric study is combined with an inquiry into the systems basis of a developmental deficit.

METHODS

General Methods and Procedures of the Experiments

All testing involved visual material, typically presented on a Macintosh computer screen. During the tasks, RP would sit comfortably at approximately 50 cm from the screen. RP used his right hand for responding when the task required key presses. RP's acuity is corrected to normal by use of glasses. All computerized tasks were administered by means of MacLab software (Costin, 1988). Most stimuli were drawings digitized by use of a Microtek Scanmaker 600ZS and edited using commercial software (e.g., Adobe Photoshop). Testing took place in multiple sessions, spanning almost 1 year in time. Control subjects were tested in those tasks where the performance of appropriate control subjects was not already known. These control subjects were 10 volunteer males matched to RP for year of birth (±2 years) and years of education (they all had a college degree). In those tasks where RT was a variable of interest, outliers were trimmed prior to the analysis of each task; outliers were defined as RTs greater than 3 *SD*s from a subject's mean RT in a particular cell (combination of levels on the independent variables).

Identifying "Famous Faces," Sex, Age, and Facial Expressions

The Famous Faces Test consists of 56 black-and-white photographs of various famous and popular figures (spanning from the 1920s to the 1990s; e.g., Charlie Chaplin, Mohammed Ali) shown on individual pages of a photo album. The stimuli used in the task were all taken from the Famous Faces Test in the "Boston Remote Memory Battery" (by M. Albert). The test has standard norms to which a subject's score can be compared. This was the only test in the whole study in which RTs were not collected. The stimuli used for the test on sex and age judgments were instead scanned black-and-white pictures from a photography art book of Alex Kayser, showing exclusively frontal views of bald men and women of different ages and races. The book is entitled *Heads* and was published by Abbeville Press in 1984. The stimuli for the Facial Expressions Test also came from a photographic reference book for artists by Erik A. Ruby, entitled *The Human Figure* and published by Van Nostrand-Reinhold in 1978.

Identifying Objects Seen at Difficult Perspectives (Noncanonical Views)

For the ''Unusual Views of Objects'' Test, 30 computer-generated drawings were selected from the ''Tarrlab object databank'' (i.e., a commercially available image databank created by Michael Tarr's research group at Brown University). Three judges (i.e., the experimenter and two research assistants) selected for each of the objects in the set only one ''odd'' object's view. Each object file was desaturated and presented in the original size for 30 msec at the center of the screen. Each trial was initiated by a press on the space bar of the computer keyboard, which caused a stimulus to appear at the center of the screen for 30 msec. The task (30 trials) was naming aloud each object. Latencies of response (RTs) were measured, from onset of each picture, with a voice-activated microphone switch.

Identifying Objects from Two-Tone Pictures (''Mooney'' Stimuli)

Thirty faces were selected from the original set of Mooney; 30 nonface objects were generated from photos of familiar artifacts or toy animals (by ''thresholding''). Several of the latter stimuli were also selected from a set of stimuli generated by Moore and Cavanagh (1998). The Mooney faces pictures (10×10 cm in size) were presented one by one in the center of the computer screen until the subject made a key press in response. As done for a previous task, in the sex judgment task, the B and N keys were labeled F and M, whereas for the age judgment, the X, C, V, B, N, M, were labeled 20, 30, 40, 50, 60, 70. All subjects performed the sex judgment first and then the age-judgment task (30 trials in each task) next. The two-tone objects were presented one by one in the center of the computer screen and were also 10×10 cm in size. The task (30 trials) was naming aloud each object. A voice-sensitive microphone switch collected RTs from the onset of each picture.

Identifying Objects at Subordinate Versus Basic Levels

Subjects viewed, in each experimental block, 12 black-and-white reproductions with six items belonging to one of two categories. There were three blocks with animal pictures and therefore six (animals) categories that were paired as follows: dogs–beetles, cows–rodents, birds–seashells. In the test, there were also two blocks with artifacts and therefore four categories, paired as follows: shoes–glasses, cars–chairs. To make the comparisons across all object kinds more controlled, an equal number of novel stimuli were used in all conditions. The test also included, in two separate blocks, matches between faces and proper names. These stimuli were 12 black-and-white photographs of human faces (novel to the subjects), divided in two equal-size categories (namely, men–women). Samples of these pictures are shown in Figure 2. At the beginning of each task, RP and controls studied in free view all the reproductions that would be seen on the computer screen. The subjects were given a few minutes to learn and/or rehearse the correct subordinate name of each animal or object, or the proper name of each person or cat. Subjects were also informed about the alternative (basic) label they would hear during the task. In the task with faces, the basic level of categorization used was the sex of each person (i.e., ''man'' or ''woman''), and proper names were only first names (e.g., ''Mary,'' ''Tim''). Each trial was initiated by a press on the space bar of the computer keyboard, which caused a fixation cross to appear at the center of screen for 500 msec. Then a stimulus appeared for 100 msec followed by the name (played by the computer) of an item. In half of the trials, the name indicated either another object in the same category or the basic label of the other paired category. In the other half of the trials, the name matched correctly the picture at either the basic or subordinate level. All conditions were counterbalanced orthogonally and conditions were presented in randomized order. Responses were recorded as key presses on the ''B'' or ''N'' keys (each key was labeled, respectively, ''yes'' and ''no''). The computer recorded latency of key presses from the offset of the target stimulus as well as the name of the key. Each experimental block had 96 trials for a total of 672 trials in the whole experiment.

Three independent judges also estimated the relative amount of curved information in each drawing on a five-step scale (i.e., 1 = mainly straight edges, 2 = more straight than curved edges, 3 = an equal amount of straight than curved edges, 4 = more curved than straight edges, 5 = mainly curved edges). These estimates were then averaged across judges and each stimulus class (e.g., chairs, dogs).

Discrimination of Straight Lines Versus Curved Lines

Stimuli in each block consisted of 48 gray shapes, constructed by filling in cells of a 4×5 grid. Each of the straight-edged stimuli was used to produce a corresponding curved stimulus by replacing the bars with gray ellipses that covered the same area. In the on/off task, a black X could appear in one of the cells of the grid, either on one of the gray-filled cells or within a blank one (i.e., off or outside of the shape). In the same/different task, both pairs of straight-edged or curved-edged stimuli could differ in the number of gray-filled cells. A trial began with a press of the space bar, which caused the screen to go blank for 1 sec. In the on/off task, a stimulus was presented on the center of the screen and remained on the screen until the subject responded by pressing either the "B" or "N" keys (each key was labeled, respectively, "on" and "off"). Instead, for the same/different task, after pressing the space bar, a pair of stimuli was presented in vertical arrangement. The task was to decide whether the top and bottom displays were identical or not. The subject responded by pressing either the "B" or "N" keys (labeled, respectively, "S" and "D"). The computer recorded the latency of key presses from the onset of every target stimulus as well as the name of the key. Trials with straight-edged or curved-edged were arranged in separate blocks of 80 trials for both the on/off and the same/different tasks. There were a total of 320 trials in the whole experiment.

Matching Depth Rotations of Cubes Versus Depth Rotations of Curved Single Surfaces ("Amoebae") and Faces

The cube stimuli consisted of geometric shapes similar to those of the classic "Shepard–Metzler" task or the Vandenberg and Kuse's (1978) Test. These stimuli were selected from another subtest of the Harvard Visuo-Spatial Battery so as to obtain three different orientations (each differing 40° of angle around the vertical axis) for each single cube assembly. For the face rotation task, stimuli were taken from the commercially available CD-ROM from Michael Tarr's laboratory at Brown University. The stimuli are originally color photos of real models, digitized by Niko Troje. Four different poses of three male and three female faces in the Tarrlab's package were rendered in black and white (to reduce skin pigmentation cues) and shown in squares each with 7.2 cm of side. The poses selected for each model face were: the one at 0° of angle (equal to a full frontal view), 30° and 60° (i.e., two different ¾ views), and 90° (equal to the precise profile view). Each photo was presented side by side on the computer screen and at equal distance from the center of the screen. There were a total of 192 trials in the test. Because each combination of factors was present in the design and the number of "same" trials was identical to that of "different" trials, in 87.5% of trials either two different faces or two different photos of the same face were shown, and in 24 of the "same" trials (12.5% of all trials), two identical photographs were shown. Each trial was initiated by a press on the space bar, which caused a stimulus pair to appear and replace the blank screen. This would remain visible until a key press on the "B" or "N" key was made (each key was marked, respectively, with an S for "same" and a D for "different") and which also would cause the reappearance of the blank screen. The computer recorded latency of key presses from the onset of the target stimulus as well as the name of the key. The curved abstract shapes or "amoebae" were the same stimuli produced by Hill and Bruce (1996); that is, computer-generated shapes created, with use of the ALIAS 3-D modeling package, by deforming points on a sphere's representation to create surface protrusions or "pseudopodia." In the current experiment, only the eight "lighted-from-above" amoebae created by Hill and Bruce were used. In both tasks, shapes were presented in pairs and side by side. In half of the "same" trials, two different orientations in depth of the same shape were presented. In the other half of the "same" trials, pairs of identical views of a same shape were shown. In "different" trials, each view of one specific shape could be matched to either view of a different shape. The occurrence of a same or different match was equally likely, and the comparison across angles of rotations of identical or different shapes was balanced. A trial began with a press on the space bar followed by the presentation of a pair of stimuli. These remained on the screen until a key press was made. The subject responded by pressing either the "B" or "N" keys (labeled, respectively, "S" and "D"). The computer recorded latency of key presses from the onset of every target stimulus as well as the name of the key. Trials with cubes or amoebae were arranged in separate blocks of 240 trials each.

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Reprint requests should be sent to Bruno Laeng, Department of Psychology, University of Tromso, Asgardveien 9, N-9027 Tromso, Norway. E-mail: bruno@psyk.uit.no.

Notes

1. A well-known clinical test developed by Benton and Van Allen (1968) requires the subject to match one target face to the same face shown in a different orientation in depth among foil faces. It is not uncommon to read in the prosopagnosia literature that the ability to match different views of faces is spared (e.g., Malone, Morris, Kay, & Levin, 1982); however, as Davidoff and Landis (1990) remark, even for those patients who are capable of matching within the (low) normal range,

this performance may be achieved via several strategies and should not be taken as evidence of normal matching or recognition of unfamiliar faces.

2. As Pinker (1997, p. 273) points out: "The only thing that *can* be special about a perception module is the kind of geometry it pays attention to, such as distance between symmetrical blobs, or the curvature pattern of 2-D elastic surfaces that are drawn over a 3-D skeleton and filled out by underlying soft pads and connectors [. . .] To call a module a face-recognizer is not to say it can handle only faces; it is to say that it is optimized for the geometric features that distinguish faces because the organism was selected in the evolutionary history for an ability to recognize them."

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