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Analysis of Errors in Color Agnosia: A Single-case Study

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Abstract

The performance of an adult with color agnosia (JT) was investigated. Although perceptual color tests clearly demonstrated no difficulty in color discrimination, multidimensional scaling analysis (MDS) revealed that naming errors were constrained to confusions of adjacent points in the three-dimensional visual semantic color space. This pattern of confusions replicated across other tasks drawing on knowledge of color concepts. The findings are interpreted as a partial disruption in mapping perceptual representations of color to prototype nodes in visual semantic color space. We propose that this methodology, already proven useful for investigation of category-specific visual object agnosia, will allow more detailed cross-case comparisons of color recognition disorders.

Introduction

Impairment of color categorization and recognition caused by neurological damage (i.e. impairment of color concepts), in the absence of deficits in color discrimination (i.e. intact color percepts), and in the absence of deficits to linguistic color terms, is known as color agnosia (Davidoff, 1991, p. 109). Despite past and continuing use of this term (e.g. Stengel, 1948; Kinsbourne and Warrington, 1964; Beauvois and Saillant, 1985; Grusser and Landis, 1991; Goldenberg, 1992), the distinction between the psychological properties of color concepts and percepts remains quite subtle due to the dependence of color concepts upon visually based qualities such as hue and saturation. We can point to their difference, however, via the following kind of example: choosing a 'good' red over a 'poor' red requires an evaluation of each color as a valid member of the relevant category, while merely discriminating between two (equally good or poor) shades of red can be accomplished entirely on the basis of perceptual mechanisms without recourse to categorical information.

Because of the subtlety of the distinction, patients with the symptoms of what could well be a color agnosia sometimes are classified as merely dyschromatopsic (Victor *et al.*, 1989, patient MS), or achromatopsic (Barbur *et al.*, 1994, patient W), terms usually reserved for patients with a perceptual impairment. In order to distinguish unambiguously between an impairment of color percepts and concepts on empirical grounds, the details of the information-processing stages involving assignment of meaning to color percepts must be specified in more detail. The present investigation develops a methodology for investigating the performance of an adult with color agnosia (JT). We begin by drawing an analogy between the processing steps required for colors and the steps mediating the identification of visual objects.

The theoretical framework for object recognition, which can be adapted for our interpretation of color agnosia, is based on three primary stages of information processing (Marr, 1982; Warrington and James, 1988). These stages occur in the following sequence: (1) construction of an internal, perceptually based description of the visual surfaces of the object; (2) access to stored structural knowledge of object forms, allowing perceptual synthesis across different viewpoints; (3) contact with conceptual, semantic knowledge of categorical and functional/associative properties of objects. After this last stage of processing, phonological representations can be accessed for object naming.

We assume that color recognition must follow a similar elaboration of information processing stages. For color recognition, stages 1 and 2 represent perceptual processes allowing accurate discrimination of hue and the maintenance of color constancy. Patients with conceptual color impairments (dysfunction at stage 3, commonly referred to as associative agnosia in the object recognition literature) can be distinguished from those with perceptual color disturbances (dysfunction at stages 1 or 2, commonly referred to as apperceptive agnosia in the object recognition literature, particularly for dysfunction at stage 2) on the following grounds: if the disorder is genuinely at the level of conceptual interpretation, and not at an earlier stage in the perceptual analysis of colors,

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then the patient should demonstrably see colors normally, but would be unable always to arrive at the correct conceptual interpretation of the percept.

While this much is clear, matters become more tentative when we attempt to uncover the details of an impairment to the conceptual mechanism that extracts color categories from vision. What more can be theorized about stage 3 in trying to analyse further the nature of color agnosia? In recent work with our colleagues (Arguin *et al*., 1996a,b; Dixon *et al*., 1997, 1998), we argued that object recognition occurs via a mapping from vision to stored intermediate representations that provide the entry points to a more elaborate semantic space. These intermediate points should be considered conceptual in nature, although they deal purely with the physical appearance of objects (e.g. the typical form of a carrot) or colors (e.g. the typical form of red). Such forms, or prototypes, are the basis for the images that we can immediately visualize, or the drawings that we can manually produce on request when given a word denoting the object (say, the word 'carrot'). Although based on visual attributes, this level of representation should not be confused with the notion of a structural description, which is widely used in computational theories of vision.

The object forms that serve as conceptual entry points to a full semantic space are based on perceptual attributes, but note that these forms are organized in terms of their semantic properties, and not purely on the basis of their physical structure. The idea of a structural description applies to a lower level of representation, whereby similarity between forms cannot be defined on the basis of semantic class. For example, a light bulb is visually similar to a pear, and would be represented as such in structural description space, but certainly not in visual semantic space.

Beyond the prototypical visual form of object exemplars like carrot and banana, there must be a further level of representation in which conceptual exemplars are arranged in terms of more abstract associative, or functional, relationships. These associations are gleaned from our unique personal and cultural experience. For example, the color red may be associated with the color green for many Canadians, due to the recent popularity of the cult comedy 'The New Red Green Show', featuring a character named Red Green. This association can arise despite the fact that red and green are visually very dissimilar. Likewise, in many cultures, carrots are often used in stews with other vegetables, such as onions. Thus, carrot and onion are related in associative/functional semantic space, but clearly, the nature of these conceptual relationships must be quite different from the relationships based on visual attributes of fruit and vegetable exemplars (physically, carrot is much more similar to cucumber or banana than to onion or potato).

The distinction that we have made between the visual representation of objects or colors in conceptual memory, and other levels of representation dealing with more abstract semantic relationships, can be glimpsed in the different kinds of errors made by certain agnosic cases. The category-specific visual agnosic ELM (Arguin *et al*., 1996a) made numerous labeling confusions within a category like fruits and vegetables, in which errors were strongly influenced by the visual similarity of the exemplars, even though, we emphasize, his ability to discriminate perceptually the differences between these forms was entirely normal (i.e. in tasks with no conceptual component). Although ELM's perceptual representations were intact, he would often confuse a banana with a cucumber, or an onion with a lemon at the conceptual level. Hierarchical cluster analysis of confrontational naming confusions led to the identification of three shape primitives that underlie the cognitive representation of many fruits and vegetables (viz. tapering, curvature and thickness). The interpretation of this result was that when mapping information from percepts to prototype concepts, structural details that normally distinguish these three shape dimensions were lost.

Although ELM's confusions were influenced purely by visual similarity, other cases with visual object agnosia produce confusion types that may be influenced more by functional/associative semantic relationships. While ELM would never confuse a banana with an apple, say, or an onion with a carrot, an agnosic whose confusions are linked to a disturbance in the associative semantic space may well produce these error types.

To summarize our argument thus far, we have noted that in analysing visual agnosia, levels of conceptual processing can be divided into those based purely on visual semantic information, as distinct from other levels of representation that include idiosyncratic or associative semantic information. Errors made by selected cases may be understood in terms of this fundamental distinction. In applying this methodology to color agnosia, we remain grounded in the distinction between processing stages that involve access to meaning (i.e. access to visual and associative semantic knowledge), and those that deal only with the construction of a visual percept. We must of course ensure that the disorder is genuinely at one or another conceptual level, and not at earlier stages limited to the perceptual analysis of colors. If this condition is indeed satisfied, then errors in the classification and labeling of hues can only be the result of a deficit confined to stage 3 in the processing stream. Given this background information, we can attempt to analyse the responses to determine where in the conceptual system the deficit lies.

Suppose the errors are exclusively associative in nature. What kind of pattern or regularity in the confusion data might we expect to see in a color agnosic? Presently, the organization of the associative semantic space for colors is poorly understood. Evidence suggests that determinants of relatedness may include frequently encountered verbal associations (e.g. red, white and blue for colors of the flag in the American culture), thematic associations (red and green for Christmas in Christian cultures), associations related to metaphoric adjectives (e.g. culturally defined color associations to political affiliations or emotions), or other contrasts (e.g. dark and light, warm and cool; Miller and

Table 1. Free-association responses to color name stimuli (normal subjects)

	Color name produced							
Color name seen	Blue	Purple	Pink	Red	Brown	Orange	Yellow	Green
Blue	–	0.00	0.13	0.16	0.14	0.00	0.16	0.29
Purple	0.16	–	0.25	0.18	0.00	0.00	0.05	0.14
Pink	0.14	0.50	–	0.24	0.00	0.00	0.05	0.06
Red	0.37	0.00	0.00	–	0.00	0.00	0.11	0.23
Brown	0.06	0.00	0.00	0.04	–	0.00	0.16	0.06
Orange	0.00	0.50	0.13	0.09	0.14	–	0.21	0.06
Yellow	0.10	0.00	0.38	0.16	0.29	1.00	–	0.17
Green	0.16	0.00	0.13	0.13	0.43	0.00	0.26	–
Number of times response produced	49	2	8	55	7	3	19	35

Table values represent the number of times the color name was produced in response to a particular color name stimulus, divided by the total number of times the response was produced (Kiss *et al*., 1972).

Johnson-Laird, 1976, pp. 333–360). Table 1 displays a matrix of free-association responses to color word stimuli (Kiss *et al*., 1972). From this we can observe the influence of associative characteristics of colors that cannot be linked to the visual properties of colors. For example, green is given in response to red more often than in response to yellow, and brown is given in response to green and yellow more often than in response to red.

Confrontational naming confusions determined by color relations based on such associative proximity would presumably produce a complex pattern that would be difficult to analyse further. In accordance with this viewpoint, several investigators of color cognition have reported that their patients committed errors that bore ‘no relation to the correct ones’ (Kinsbourne and Warrington, 1964, p. 297), showed ‘no consistency’ (Geschwind and Fusillo, 1966, p. 139), were ‘difficult to understand’ (Beauvois and Saillant, 1985, case MP, p. 24), ‘seemed very strange’ (Beauvois and Saillant, 1985, case MP, p. 14), or produced ‘wrong names at random’ (De Vreese, 1987, p. 117).

On the other hand, if the confusions produced by a color agnosic are influenced purely by visual semantic relationships, they should be open to interpretation. This is because many details regarding the nature of visual qualities of colors have been specified. The primitive dimensional constituents of a three-dimensional visual semantic color space have been defined (Helm, 1964; Heider and Oliver, 1972; Wish and Carroll, 1974; Offenbach, 1980; Shepard, 1992; Shepard and Cooper, 1992), prototypical colors have been identified (Heider, 1972; Heider and Oliver, 1972; Rosch, 1973), and standardized color chips have been created that are believed to match these prototypes (Heider, 1972; Boynton and Olson, 1987).

Owing to the fact that the underlying primitives and prototypes of the visual semantic color space are largely understood, we can select test materials that represent combinations of values along visual color space axes, thus allowing the visual similarity of test exemplars to be specified with empirical precision. These tools allow the confrontational naming confusions made by the appropriate case of color agnosia to be interpreted within the context of the organized visual semantic color space. If this visual semantic color space has become unstable, or has been altered in some other way, we would expect a meaningful pattern of errors to surface on any task that draws on the information coded within this space.

In the present investigation, we begin with a case history, and a broad neuropsychological assessment of a remarkable color agnosic, JT. We test the peripheral (input and output) components of his color cognition, namely, linguistic color terms and his ability to detect color contrasts (color perception). Finally, we investigate three types of tasks thought to draw upon color concepts: confrontational naming, color–name matching and three purely visual color tasks. We interpret the confrontational naming errors, and errors from other cognitive tasks, within the context of contemporary theories of the color mechanism. In the discussion, we consider the applicability of this methodological approach to theories of the multidimensional representation of visual stimuli.

Case history

The consent of JT and control subjects to the collection and publication of these results was obtained according to the declaration of Helsinki. On 4 January 1991, JT became suddenly comatose. A CAT scan revealed a massive intraventricular hemorrhage secondary to an arteriovenous malformation situated at the medial aspect of the left occipital horn. At the time of the first CT scan, there was a 2 mm shift of the septum pellucidum to the right of midline. A ventricular shunt was inserted into the anterior horn of the left lateral ventrical. The arteriovenous malformation was surgically resected on 14 February 1991.

Prior to the hemorrhage, JT worked as an electronics technician with college education. Since this hemorrhage, he has been unable to work. JT reported that he previously suffered a similar episode that was treated in a Mexican hospital. At the time of this investigation, JT was 29 years old. In addition to color cognition difficulties, at the time of testing JT suffered from a right hemianopia, and pure alexia. Previously, JT had suffered from visual object agnosia (which was more severe for specific categories such as biological objects), the severity of which was minor at the time of testing.

Neuropsychological assessment

Behavioural observations

JT was fluent in English, his second language (Spanish is his first language). He tended to digress from the topic of discussion, and was somewhat vague in relating parts of his history (e.g. he stated that he was ‘about 30’, and was unsure which side of his body had been paralysed). His speed of processing was slowed, such that the evaluation required significantly more time than expected. He was also easily fatigued.

General intellectual functioning

General intellectual functioning, as measured by the Wechsler Adult Intelligence Scale – Revised, fell in the borderline range overall [Full-Scale IQ fell at the sixth percentile (%ile)]. Verbal intellectual skills such as general fund of knowledge, vocabulary, social judgement/common sense (a strength: 91st %ile), and abstract thinking fell in the average range overall (Verbal IQ fell at the 29th %ile). In contrast, non-verbal skills were severely impaired (Performance IQ fell at the first %ile). On the various visual subtests, JT experienced difficulties attending to visual details (first %ile), arranging pictures in logical sequence (ninth %ile) and assembling puzzles (below the first %ile). His ability to reconstruct designs using blocks was relatively preserved (16th %ile: low-average range). His drawings of three-dimensional objects—a house and a cube—were also within normal limits.

Attention/Concentration

The Attention/Concentration Index of the Wechsler Memory Scale–Revised (WMS–R) fell at the first %ile. Digit span was low–average in both forward and backward directions (the maximum number of digits repeated was five forward and three backward). Visual span was borderline in the forward direction (five digits) and low-average/borderline backwards (four digits). Speed of information processing was extremely slow (below the first percentile) as measured by a digit–symbol substitution task. JT appeared to be prone to losing his place on the page during tasks requiring visual attention; this may be an effect of his hemianopia. Inattention to the right visual field was noted in one instance during a design memory test.

Handedness

JT’s responses to the Annett Handedness Questionnaire indicated mixed handedness.

Language

Word generation in response to phonemic cues was intact (Controlled Oral Word Association Task: 55–59th %ile). Confrontational naming, as measured by the Boston Naming Test, was severely impaired (33/60; below the first %ile). JT tended to circumlocute (i.e. to describe the use of an object) when he failed to name an object. Given a semantic fluency test, he named only eight animals in 1 min; a young adult would be expected to generate at least 14 animal names on this task.

Memory

An index of learning and immediate recall (General Memory Index: WMS-R) fell in the severely impaired range (below the first %ile). Memory was impaired for both verbal and visual material. Recall of stories and of designs fell in the borderline to impaired range both immediately and following a delay. Encoding of visual associations was extremely poor: given six presentations of the same six colour–shape pairs, his recall across trials was 0-1-1-4-2-1. Similarly, although he was able to recall simple, overlearned verbal associations (e.g. ‘baby-cries’, ‘rose-flower’), he failed to learn any of four novel (i.e. semantically unrelated) associations, even given six exposures to the material. When provided with a multiple-choice format, however, he correctly recognized 3/4 of the words that had not been recalled. This suggests retrieval difficulties. Memory weakness is further suggested by the fact that his orientation to time was deficient: he was able to name the year, but failed to identify the month, date, day of the week, and his own exact age.

Color cognition assessment

In color agnosia, the peripheral components of the color cognition system (i.e. those important for perceptual color processing and language) are functioning normally, while the central components (for conceptual color processing) are not. In our assessment of the color agnosic case JT, we first tested the peripheral components of color cognition. Analysis of error types was then used to assess the hypothesis that a dysfunction in conceptual processing was responsible for the pattern of errors in confrontational naming, color–word matching, and ‘purely visual’ color tasks.

Chromatic processing

The color contrast sensitivity function assesses visual thresholds for the detection of red–green sinewave gratings (horizontal bar patterns) which can be seen only on the basis of their color contrast. Such stimuli are termed isoluminant because they contain no achromatic contrast: they do not stimulate the luminance detection mechanisms of the visual pathways and are detected only by chromatic mechanisms of the early cortical pathways. Successful performance of this task would not be possible for a patient who has suffered damage to the brain areas directly sensitive to the wavelength distribution of light (i.e. an achromatopsic patient).

Participants, materials and procedures

The figures in the Ishihara plates were readily identified by JT at 60 cm and 2 m viewing distance. Subsequent investigation involved comparison of JT's color contrast sensitivity function with previously published data (Mullen, 1985) on control subject KTM. Since a chromatic deficit might be confined to a particular spatial scale, JT's detection thresholds for the isoluminant stimuli were measured over a range of spatial frequencies (bar widths), thus assessing performance over the full range of spatial scales that are relevant for color vision (Mullen, 1985). By the same token, we also assessed his chromatic detection at two temporal frequencies using contrast reversing gratings of 1 and 10 Hz. Further details of the methods used for measuring color contrast sensitivity can be found in Mullen *et al*. (1996).

Results

The top panel of Figure 1 shows the results for color contrast sensitivity measured at 1 Hz of counterphase flicker. Data demonstrate that JT was well able to detect the chromatic grating patterns at all spatial frequencies (bar widths). This shows that JT's color contrast sensitivity is close to that obtained from a normal participant. Moreover, he displays the characteristic lowpass shape of the normal color contrast sensitivity function (Mullen, 1985). The somewhat lower overall sensitivity of JT (about 0.2 log units) is not surprising since he is an hemianope with a partial loss of foveal and complete loss of parafoveal vision on the affected side.

The lower panel shows results obtained at 10 Hz of counterphase flicker. The color contrast sensitivity of JT is compared to previously published data on the same normal participant (Mullen and Boulton, 1992) measured under similar conditions. There is no difference between the abnormal and normal participant in this case: in fact, in some instances, JT's color sensitivity rises above that of the normal. The greater similarity between the normal and abnormal contrast sensitivities at 10 Hz compared to 1 Hz is not surprising, since at 10 Hz detection thresholds are less dependent on foveal and paracentral vision (Allen and Hess, 1992).

Discussion

JT does not suffer from an impairment of color contrast sensitivity. He is as well able to use color contrast to detect the presence of objects or patterns as someone with normal color vision, taking into consideration his hemianopia. For example, he was able to count accurately the red and green bars of the test grating pattern and referred to them as 'colored'. We also considered the possibility that although his threshold vision is normal, his suprathreshold contrast perception is impaired. We measured JT's contrast discrimination for the full contrast range using 1 c.p.d., 1 Hz test gratings. These results confirmed that JT is able to discriminate suprathreshold color contrast normally. These results indicate that his primary processing of color contrast is intact, and that he cannot be considered achromatopsic.

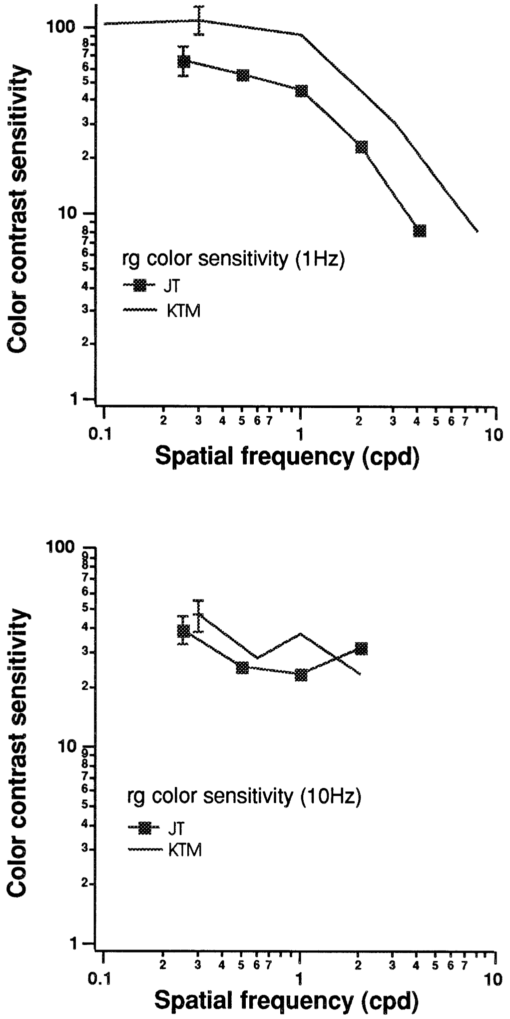

Fig. 1. Color contrast sensitivity of JT compared to control subject KTM.

The color lexicon

The state of the color terms in the phonological output lexicon can be tested independently of the visual semantic color space. The pure production of color names was tested in two ways: (i) by asking JT about color name–abstract concept associations (e.g. green with envy; Beauvois and Saillant, 1985); (ii) by asking JT about well-known object–color associations (e.g. green grass).

Participants, procedure, results and discussion

JT was asked to complete verbally fill-in-the-blank sentences with a color name (e.g. 'When someone is very envious,

Table 2. Tests of linguistic color terms

Task performed	Date	% Correct
Use of color names in fill-in-the-blank sentences[a]	12/95	100 (4/4)
Stating the color of familiar objects[b]	12/95	100 (13/13)

[a] Sentences used: 1) When you sell something illegally, you sell it on the _____ market (black). 2) You can get _____ fever from mosquitoes (yellow). 3) When a person is a coward, they are said to be _____ (yellow). 4) When a person is very envious, they are said to be _____ with envy (green).

[b] Objects tested: banana, penguin, sheep, ocean, fir tree, carrot, cigar, elephant, chick, chocolate, lips, grass, leaf.

Table 3. OSA color chip coordinates for naming session one

Color	Exemplar 1	Exemplar 2
Blue	0 -2 2	-1 -3 3
Purple	-2 -2 -2	-3 -3 -1
Pink	1 -1 -5	n/a
Red	-3 1 -7	-4 2 -6
Brown	-3 3 -3	-4 2 -2
Orange	0 6 -6	-1 5 -7
Yellow	2 8 -2	3 9 -1
Green	0 4 2	-1 3 3

they are _____ with envy'; answer: green), and was asked to state the color of familiar objects. On both tasks, he provided the correct color for 100% of the trials (see Table 2, first and second sets of results). These results demonstrate that there is no dysfunction specific to colors at the level of the language system. In consideration of this result, and the failure to detect a perceptual deficit for colors, further efforts were concentrated on testing the processing of colors at a conceptual level.

Confrontational naming

Color naming involves transferring information from conceptual color-processing mechanisms to the phonological output lexicon (Davidoff, 1991, p. 106). Naming confusions can shed light on the nature of this conceptual dysfunction, due to the dependence of color naming on intact conceptual color processing,

Participants, materials and procedures

Color naming data were collected on two occasions under differing conditions. Testing session one took place in July 1993. Optical Society of America (OSA) color chips were presented to JT four times each in daylight on a gray background. The OSA coordinates and their corresponding color names are listed in Table 3. If no response had been recorded before 2 min had passed, JT was encouraged to respond.

Testing session two took place in December 1995 and March 1996. All color patches were displayed simultaneously on an Apple ColorPlus 14 inch color monitor. The patches used were those chosen most frequently (from a screen display of 32 choices per color) by a pre-experimental group of 12 participants (with normal color vision) to be most representative of the given color. The experimenter pointed to one of the patches (in random order), and requested one color name from JT. A name was requested four times from each color patch. There was no time limit imposed for these sessions.

Results

Overall, naming performance was quite poor. JT scored 51% correct over both sessions (45/92). Color naming responses are listed in Table 4 as the percentage of number of presentations. PROC MDS of the SAS System for Windows Release 6.10 (Statistical Analysis Systems Institute, 1994) was used to find structure underlying these naming confusions. A three-way non-metric multidimensional scaling (MDS) model was fit, where the testing occasions were treated as individual sources data (the 'third way'; Arabie *et al*., 1987). The three-way generalization of Kruskal's stress formula 1 (Kruskal, 1964) was the badness-of-fit measure minimized. The optimal fit of the data to distances was found by way of a non-linear least squares algorithm.

Using stress as a guide to dimensionality (Kruskal and Wish, 1978, pp. 53–56), the number of dimensions retained was three. The three dimensions that were found to underlie errors from both naming sessions corresponded closely to those that determine the normal visual color space: red–green (RG), purple–yellow (PY) and brightness (B). The axis coordinates resulting from this analysis are listed in Table 5.

The overall fit (stress = 0.0), and the fit for each individual testing session (stress = 0.0), was very precise (Kruskal, 1964; see Table 6). Also listed in Table 6 are dimension coefficient sizes. The larger weights for the RG and PY dimensions indicate that confusions were made more frequently on these dimensions than on the B dimension. The color proximities in JT's confusion space, as computed from this MDS model, are visually presented in Fig. 2 for the two most influential axes (RG and PY).

Discussion

The MDS results indicate that the confusions JT made when naming colors are largely constrained by the normal visual color space axes. Proximal areas of the visual color space were much more likely to be confused. More detailed consideration of the theoretical implications of this result will be presented in the General discussion.

Note that there were some stimulus weights that did not fit this interpretation: (i) the high weight of orange on the PY dimension; (ii) the low weight of purple on the brightness dimension. It may be that a larger collection of naming confusions may cause these anomalous weights to disappear. If this is not the case, other explanations may lie in the fact that there are some unusual qualities, in comparison to the

Table 4. Confrontational color naming responses for sessions one and two

	Response							
Color viewed	Blue	Purple	Pink	Red	Brown	Orange	Yellow	Green
Session one								
Blue	50	0	0	0	25	0	0	25
Purple	0	100	0	0	0	0	0	0
Pink	25	50	25	0	0	0	0	0
Red	0	25	0	0	75	0	0	0
Brown	0	13	0	0	74	0	0	13
Orange	0	0	0	13	13	64	38	0
Yellow	0	0	0	0	0	13	74	13
Green	0	0	0	0	0	0	0	100
Session two								
Blue	25	0	0	0	0	0	25	50
Purple	0	75	25	0	0	0	0	0
Pink	0	75	0	25	0	0	0	0
Red	0	25	0	0	50	25	0	0
Brown	0	25	0	25	50	0	0	0
Orange	0	0	25	0	75	0	0	0
Yellow	0	0	0	0	0	0	25	75
Green	0	0	0	0	0	0	0	100

Values represent the percentage of trials in which the response was given to the viewed chip. In session one, pink was presented four times, and all other colors were presented eight times. In session two, all colors were presented four times.

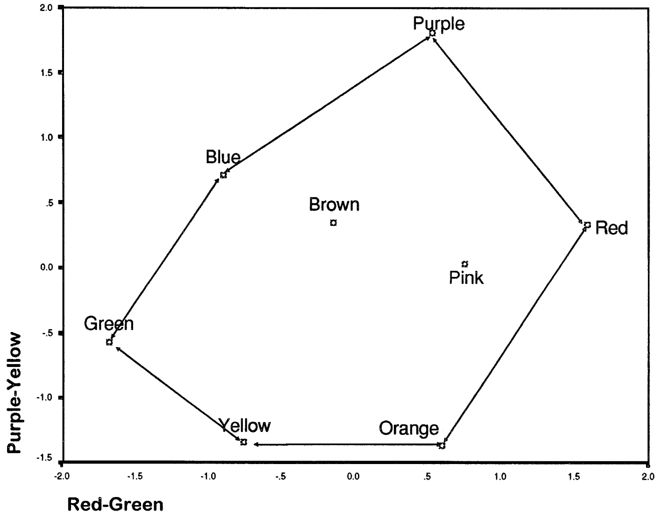

Fig. 2. Graphical representation of the pattern underlying JT's color naming confusions. The red–green dimension is plotted against the purple–yellow dimension. Newton's color circle has been superimposed.

other colors, about orange and purple. Regarding orange, there is some evidence that orange is not, in fact, a focal color (Sternheim and Boynton, 1966). Irregularities regarding purple include: (i) this is the least frequently used of the focal color terms (Kucera and Francis, 1967); (ii) this color term is used least reliably by children, suggesting late acquisition (Heider, 1971). Thus, these colors may be represented in the visual semantic color space with less stability than the others. Generally, however, there was remarkable concordance of the axes underlying these naming confusions with the normal visual color space axes.

Table 5. Coordinates of configuration for colors on dimension axes

	Dimension		
Color	Red–green	Purple–yellow	Brightness
Blue	–0.90	0.72	0.88
Purple	0.54	1.81	0.14
Pink	0.76	0.04	1.43
Red	1.59	0.34	–0.85
Brown	–0.14	0.36	–1.45
Orange	0.60	–1.36	–0.51
Yellow	–0.76	–1.34	1.19
Green	–1.68	–0.56	–0.82

Table 6. Dimension coefficients and fit statistics on naming sessions one and two

		Dimension coefficients		
Session	Fit[a]	Red–green	Purple–yellow	Brightness
Session 1	0.00	1.15	1.02	0.80
Session 2	0.00	1.18	1.00	0.79

[a] Kruskal's stress formula one.

Matching visually presented colors to auditorily presented color names

On the hypothesis that JT suffers from a dysfunction of the visual semantic color space that does not involve a language deficit, the confusions for color–word matching should match those found in the naming tasks.

Table 7. False-positive response types for matching visually presented colors to auditorily presented color names

	Color name heard							
Color viewed	Blue	Purple	Pink	Red	Brown	Orange	Yellow	Green
Blue	–	0	0	0	25	0	0	50
Purple	0	–	0	0	50	0	0	0
Pink	75	100	–	0	50	25	0	0
Red	0	0	75	–	100	50	0	0
Brown	25	0	0	0	–	0	0	0
Orange	50	0	75	0	25	–	50	0
Yellow	25	0	0	0	0	0	–	0
Green	25	0	0	0	0	0	0	–

Values represent the number of times a false-positive response type was given divided by four (four being the total number of trials each chip/name pairing occurred).

Participants, materials and procedures

Color–word matching data were collected in November 1993. Each OSA color chip was presented to JT eight times in daylight on a gray background. When the chip was placed down, the experimenter said a color name. JT was then asked to indicate whether or not the color chip matched the color name. Each color chip was presented with each of the eight focal color names. The OSA coordinates of the color chips, and their corresponding color names, are listed in Table 3.

Results

JT produced 36% false positives (35/96) and 3% false negatives (1/32), with an overall percentage correct of 72% (92/128). Color–name matching confusions (false positives) are listed in Table 7 as the percentage of confusions out of the four times that each chip/name pairing occurred.

To test the hypothesis that the pattern underlying the name–chip same–different judgment confusions matched those underlying the naming confusions, PROC MDS of the SAS System for Windows Release 6.10 was used to carry out confirmatory three-way MDS. For this procedure, a hypothesized configuration was specified, and the program set for zero iterations (Kruskal and Wish, 1978, p. 69). The three-way generalization of Kruskal's stress formula 1 (Kruskal, 1964) was the badness-of-fit measure that tested this hypothesis. The fit for this hypothesized configuration (stress = 0.05, classified as 'good' by Kruskal, 1964) indicated that the pattern underlying the color–word matching confusions was essentially equivalent to that from the naming confusions.

Discussion

The MDS results demonstrate that the confusions JT made on the name–chip same–different judgment task were, as was the case for color naming, largely constrained by the normal visual semantic color space axes. Again, proximal areas of the visual semantic color space were much more likely to be confused.

Purely visual tasks

Beauvois and Saillant (1985) presented an argument claiming that tests can be constructed for which successful performance depends almost wholly on the functioning of the visual semantic color space, minimizing the contribution of the language system. In their words, the stimuli must be visual, the intervening process visual (e.g. visual imagery) and the response non-verbal. A visual (i.e. non-verbal) color response is one where the response is not a color name. These authors argued that successful performance on these 'purely visual tasks' provides the most pure measure of the status of the visual semantic color space.

Note that there is some controversy regarding the ability of the experimenter to control the 'visual purity' of the intervening process, that is to say, avoidance of linguistic strategies. A reliable method of controlling the strategy of subjects is not readily available. Beauvois and Saillant (1985) attempted to remind their subjects to avoid linguistic strategies by sticking adhesive plaster on their mouths. Instead of attempting to control subject strategy, we simply assumed that purely visual tasks gave a more pure measure of visual semantic color space integrity than color naming or color–word matching, by minimizing the influence of linguistic processes.

The three visual tasks employed in this study were color categorization, the coloring of line drawings and pointing out the correctly colored object from a set of five. If the pattern of confusions resulting from these visually pure tests agrees with that resulting from the tests that may have involved language to a greater degree, this will provide further evidence that the common dysfunctional component is the visual semantic color space.

Participants, materials and procedure

Color categorization. JT and two control participants with self-reported normal color vision participated in this experiment. JT and control participant one categorized four sets of color patches displayed on an Apple ColorPlus 14 inch color monitor in February and March 1996. Sets one and two consisted of patches representing four colors only (red, green, blue and yellow). Set one consisted of 16 color patches, four examples of each color, varying in hue and brightness. Set two consisted of 32 patches, eight of each color. Sets three and four both contained 32 patches, four examples of each of eight colors (red, green, blue, yellow, orange, brown, pink and purple). They differed only in the specific color patches they contained.

Participants were asked to use the mouse to place these patches into color categories. The computer screen was sectioned off into the correct number of categories, but the participants were not specifically told to use these sections for sets one, two or three. For set four, participants were told they must use the eight partitions on the screen.

In July 1996, JT and control participant two were tested on two sets of 32 color chips, with eight examples of each color category (set five and set six). These chips were chosen by the experimenters to fit eight color categories (red, green, blue, yellow, orange, brown, pink and purple), and were presented on a gray background in daylight (not on a computer screen, as was the case for sets one–four). On set five and set six, control participant two was asked to sort the chips into as many piles as he wished. On set five, JT was asked to sort the chips into as many piles as he wished. On set six, JT was instructed to sort the chips into exactly eight categories, with four chips per category.

Coloring line drawings. JT was the only participant in this experiment. Line drawings of 22 objects were presented in groups to JT, along with 24 colored pencils. He was instructed to color the line drawing with the pencil that was closest to the color normally associated with the object. There was no time limit imposed for this task.

Choosing the correctly colored object. JT was the only participant in this experiment. Five line drawings of each of 10 objects were presented in groups to JT, where only one of the five was colored correctly. He was instructed to point to the line drawing that was colored correctly. There was no time limit imposed for this task.

Combined results

For the categorization testing sessions, the categorization of the control participants matched that expected by the experimenters. The percentage correct for JT on the categorization task was not a straightforward calculation, but the upper bound was 91% correct (159/176) and the lower bound 88% correct (155/176). Detailed verbal descriptions of the categorization errors are listed in Table 8. When coloring line drawings, JT's percentage correct was 73% (16/22; see Table 9), and when choosing the correctly colored object from five choices, JT's percentage correct was 60% (6/10; see Table 10).

Some characteristics of these data made the analysis of confusions using MDS impossible. First, for practical reasons, it was not possible to provide foils that guaranteed equal representation of all potential confusions on the task involving pointing to the correctly colored object. Thus, a confusion matrix based on this experiment would be biased towards the foils presented.

Secondly, for both the task involving coloring line drawings, and the task involving pointing out the correctly colored object, selection of test materials was restricted to objects that are generally considered to occur in only one color. In keeping with the intention of discouraging the involvement of the language system, an additional restriction was the avoidance of objects eliciting strong verbal object–color name associations. These restrictions cause the distribution of test exemplars to be unequal over color categories, again biasing potential confusions. Finally, the proper method of tallying confusions in the categorization task was not obvious, as some errors involved a refusal to categorize, and others a collapsing of entire color categories. Because of these biases, analysis of the errors on the visual tasks was made at a more descriptive level, pooled over the three tasks.

Figure 3 displays the number of overall confusions for color pairs plotted against the rank of pair similarities computed from the MDS model fit to naming confusions (predicted similarities were averaged over the individual test sessions). Similarly, Fig. 4 displays the number of tasks on which the confusions were made plotted against rank of pair similarity. The Spearman correlation between pair similarity and the total number of confusions (Fig. 3) was –0.76 ($P < 0.001$). Similarly, the Spearman correlation between pair similarity and the number of tasks on which the confusions were made (Fig. 4) was –0.77 ($P < 0.001$). These figures demonstrate a clear trend towards increased confusions on pairs likely to be confused in confrontational naming and the color–name matching tasks. Color similarity in the three-dimensional space that resulted from the confrontational naming analysis, and confusion tallies, are listed in Table 11.

Discussion

Performance on the purely visual tasks allowed us to test the hypothesis that the observed confrontational naming errors, and the observed color–name matching errors, resulted from a dysfunction at the level of the visual semantic color space, while minimizing the influence of language. A clear trend towards more frequent confusion of color pairs that were also confused in color naming and color–word matching was demonstrated. We can conclude that a dysfunction at the level of the visual semantic color space appears to underlie all color test results displayed here, and is perhaps the cause of all color cognition deficits presented by JT.

General discussion

Color agnosia is traditionally thought to arise from a dysfunction of the 'color space' (Davidoff, 1991, p. 109). In this manuscript, we expand on this model, and distinguish between the visual semantic color space and the associative semantic color space, whereby the representations of prototypical

Table 8. Color categorization results

Date	Set	No. of chips	No. of color categories by control	No. of categories instructed to be used by JT	No. of chips not categorized	No. of categories formed	No. of chips placed in incongruous category	No. of chips correctly categorized
2/96	1	16	4	n/a	0	4	0	16
2/96	2	32	4	n/a	0	4	0	32
2/96	3	32	8	n/a	2[a]	6[b]	3[c]	19–23[d]
3/96	4	32	8	8	0	8	2[e]	30
7/96	5	32	8	n/a	2[f]	8	1[g]	29
7/96	6	32	8	8	0	8	3[h]	29

[a] One brown chip, one purple chip not categorized.

[b] All red and orange chips placed together in one category, purple chips spread over other categories.

[c] One purple chip in blue category, one purple chip in brown category, one purple chip in pink category.

[d] Lower bound (19) if all chips in the merged red–orange category are considered incorrectly categorized, upper bound (23) if four of the eight chips in the merged red–orange category are considered correctly categorized.

[e] One brown chip in purple category, one purple chip in brown category.

[f] One light green chip, one tan-colored chip not categorized.

[g] One pink chip in purple category.

[h] One red chip in brown category, one brown chip in pink category, one pink chip in red category.

colors in visual semantic color space serve as conceptual entry points to associative semantic color space.

Our interpretation of the present case promotes the recognition that errors arising from dysfunction at the level of the visual semantic color space follow a pattern that reflects the organization of this space. More specifically, for JT, the adjacent regions of the visual semantic color space were much more likely to form confusions than distant regions of the visual semantic color space. We now consider how this set of results can be integrated into recently developed theoretical accounts of multidimensional representation of visual stimuli.

Application and expansion of the simple distance model of object categorization (Smith and Medin, 1981, pp. 107–110) has proven fruitful in the area of computational models of human perception and conception of visual stimuli (e.g. Kruschke, 1992; Cutzu and Edelman, 1995, 1998; Edelman, 1995, 1998). This approach assumes that a series of stages of visual information processing can be thought of as translations of points between independently functioning, metric, multidimensional spaces. This abstraction of cognitive concepts to space transformations can lend precision to language when discussing distinctions between perceptual and conceptual cognitive representations, and the operations involved in categorization of viewed stimuli. Although this language was developed for use with object recognition, we will use these terms to specify operations of color recognition.

The perceptual multidimensional representation space is based on axes that code the most basic elements of colors, such as the responses of cytochrome oxidase ‘blobs’ to retinal input (Davidoff, 1991). The collection of representation points at this level of analysis has been termed the measurement space by Edelman (1998), and is thought to be of extremely high dimensionality. This measurement space represents the basis for what we have termed ‘color percepts’ in the Introduction.

Visual semantic representation space is of much lower dimensionality than perceptual representation space, as visual semantic representation space is based only on axes relevant for categorization. Pre-designated points in this space represent prototypical colors, and categorization proceeds by computation of the distance of the point representing the viewed color to points representing prototypical colors. Edelman (1998) describes this measure of distance (i.e. similarity) as the activation output of a ‘classifier node’. The viewed color is classified with the prototype to which it is the most proximal. In this way, the prototypical colors in visual semantic color space serve as conceptual entry points to associative semantic color space. Thus, as has long been claimed (e.g. Shepard and Chipman, 1970), cognitive encoding of visual stimuli in conceptual representation space appears to draw upon similarity codes.

Table 9. Results from coloring line drawings

Object	Correct response	Correct response given?	JT’s response
$2 bill	brown	no	orange
$5 bill	blue	yes	
$10 bill	purple	no	red
$20 bill	green	yes	
$50 bill	red	no	pink
Artichoke	green	yes	
Asparagus	green	yes	
Banana	yellow	yes	
Barrel	brown	yes	
Carrot	orange	no	red
Cherry	red	no	orange
Chocolate	brown	yes	
Cigar	brown	yes	
Eggplant	purple	yes	
Flamingo	pink	yes	
Jack-o-lantern	orange	no	red
Lips	red	yes	
Orange	orange	yes	
Tomato	red	yes	
Tree	green	yes	
Violin	brown	yes	
Watermelon	red	yes	

Table 10. Results from choosing correctly colored drawing

Colored object	Correct response	Foils	Correct response given?	JT's response
Carrot	orange	yellow, brown, blue, red	yes	
$5 bill	blue	red, brown, purple, green	no	green
$10 bill	purple	brown, blue, green, red	no	brown
Asparagus	green	yellow, light green, dark green, pink	no	yellow
Cigar	brown	red, orange, pink, gray	yes	
Watermelon	red	orange, yellow, blue, green	yes	
Strawberry	red	purple, brown, yellow, orange	yes	
Pig	pink	brown, red, orange, purple	yes	
Lemon	yellow	white, tan, green, red	yes	
Football	brown	red, green, yellow, orange	no	red

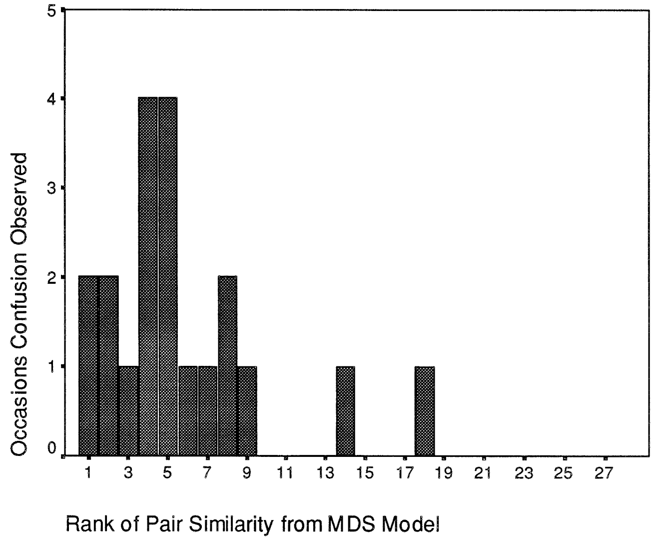

Fig. 3. Pooled number of color confusions on 'purely visual tasks', plotted as a function of proximity in the three-dimensional space that resulted from MDS analysis of confrontational naming confusions (from Table 11).

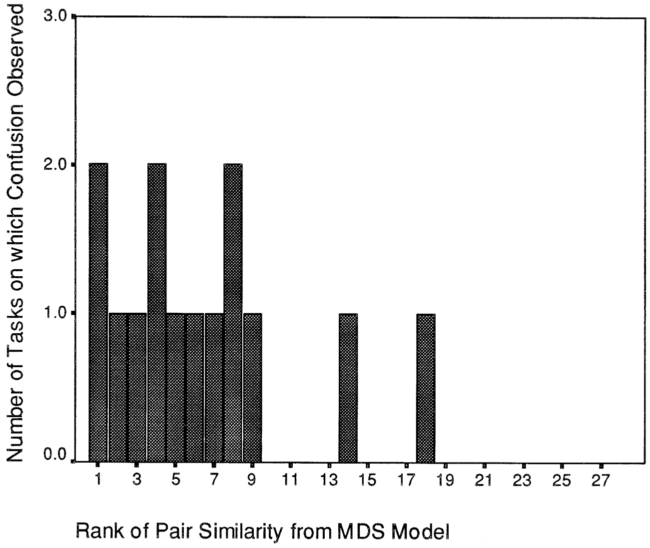

Fig. 4. Number of 'purely visual tasks' on which color confusions were made, plotted as a function of proximity in the three-dimensional space that resulted from MDS analysis of confrontational naming confusions (from Table 11).

In order for these 'distance computations' of similarity to prototypes to be carried out, the high-dimensional perceptual space representation must be translated into a representation of the same dimensionality as the prototype representations (i.e. the dimensionality of the visual semantic color space). This dimension reduction step is analogous to the transformation from high-dimensional 'variable space' to low-dimensional 'factor space' commonly carried out in psychological research whenever factor analysis is used. The axes of the low-dimensional visual semantic color space are well known as red–green, blue–yellow and brightness. The values, for the viewed color, on visual semantic color space axes can be thought of as the output activity of three cognitive 'modules' sensitive to these color contrasts.

Use of these concepts allows any point in visual semantic color space to be specified by q values on q axes, where q is the dimensionality of the visual semantic color space ($q = 3$). This collection of q values can be referred to as a vector representing this point in visual semantic color space. Each viewed color is encoded by a visual semantic representation vector with components equal to excitations of q respective neuronal modules.

Similarly, each prototypical color can be described by its visual semantic representation vector. Using representation vector terminology, color categorization can be understood by the following analogy: the distance from the viewed color representation to all prototype representations is the inner product of the representation vectors (or another measure of similarity; see Edelman, 1998, p. 17). The viewed color is then categorized with the prototype to which its representation in visual semantic color space is most proximal, and identification proceeds by mapping this prototype point (or exemplar node) in visual semantic color space to the associative semantic color space, and the language system.

Although JT has normal color contrast processing, his response variations are based on visual similarity. This pattern of errors can be explained by postulating that distance computations (i.e. measure of similarity) of the color representation vectors to the prototype representation vectors are perturbed by noise. In this way, the computed distances of the viewed color to prototypes are perturbed, but only enough to cause the activated prototypes to be constrained to the few

Table 11. Color pair similarity in the three-dimensional space that resulted from MDS analysis of confrontational naming confusions, and confusion tallies for purely visual tasks

Similarity ranking based on MDS distances	Color pair	Distance computed from MDS model	Number of confusions between color pair terms, pooled over purely visual tasks	Number of purely visual tasks for which color pair confusions were present
1	Red–brown	2.0646	2	2
2	Purple–pink	2.0717	2	1
3	Yellow–green	2.0735	1	1
4	Red–orange	2.0740	4	2
5	Purple–brown	2.0749	4	1
6	Blue–green	2.0750	1	1
7	Purple–red	2.0751	1	1
8	Pink–red	2.0752	2	2
9	Brown–orange	2.0756	1	1
10	Blue–brown	2.0766	0	0
11	Orange–yellow	2.0866	0	0
12	Brown–green	2.0873	0	0
13	Pink–orange	2.0903	0	0
14	Blue–purple	2.0914	1	1
15	Blue–yellow	2.0957	0	0
16	Blue–pink	2.1023	0	0
17	Pink–yellow	2.2610	0	0
18	Pink–brown	2.5287	1	1
19	Orange–green	2.7924	0	0
20	Brown–yellow	2.8006	0	0
21	Blue–orange	2.9448	0	0
22	Purple-orange	3.2292	0	0
23	Blue-red	3.2354	0	0
24	Pink–green	3.4125	0	0
25	Purple–green	3.6030	0	0
26	Red-yellow	3.6044	0	0
27	Purple–yellow	3.6128	0	0
28	Red–green	3.9168	0	0

with the greatest similarity to the viewed color. Under these conditions, a matrix of confusions will be based on visual similarity. Moreover, this pattern of confusions will be observed for any task relying on cognitive representations of colors in the visual semantic color space.

Thus, within the context of representation vector theory, JT's pattern of confusions on color recognition tasks can be explained as a dysfunction in distance computation to prototype nodes at the level of the visual semantic color space. With this groundwork in place, we believe that future investigation of color cognition disorders would benefit from analysis of confrontational naming confusions within this theoretical framework.

As a final point, we should note that the traditional case study approach to color cognition disorders has focused on 'disconnection syndrome' explanations (e.g. Geschwind and Fusillo, 1966; Oxbury *et al*., 1969; Mohr *et al*., 1971; Meadows, 1974; Damasio *et al*., 1979). We suspect that the widespread application of this approach may have detracted from more precise analyses of patient errors. For example, although Mohr *et al*. (1971) noticed that their color agnosic patient's errors 'were not random but bore a relation to the correct response', no further analysis was carried out, and the authors concluded that the deficit was 'more a 'dysrelation' than a 'disconnection' between colors and their names' (p. 1112). A review of the literature suggests that patients making errors similar to JT have been observed (e.g. Mohr *et al*., 1971; Beauvois and Saillant, 1985, case RV; Victor *et al*., 1989, case MS; Goldenberg, 1992, case K. Qu.), but confusion matrices were not published or analysed.

De Vreese (1987, p. 111) noted (with disapproval) that there is a prevalence of the opinion that 'naming on a confrontational task is of little diagnostic value' for discriminating varieties of color recognition disorders. In this investigation, we have demonstrated that, on the contrary, an increased focus on error analysis (e.g. color naming confusions) seems a promising path to follow for expansion on the nature of cognitive representation of color, and color agnosia in particular. At the very least, publication of color naming confusion matrices (e.g. Davidoff and Ostergaard, 1984, p. 420) would allow more detailed across-case comparisons of color recognition disorders.

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Analysis of errors in color agnosia: a single case study

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Abstract

The performance of an adult with color agnosia (JT) was investigated. Although perceptual color tests clearly demonstrated no difficulty in color discrimination, multidimensional scaling analysis (MDS) revealed that naming errors were constrained to confusions of adjacent points in the three-dimensional visual semantic color space. This pattern of confusions replicated across other tasks drawing on knowledge of color concepts. The findings are interpreted as a partial disruption in mapping perceptual representations of color to prototype nodes in visual semantic color space. We propose that this methodology, already proven useful for investigation of category-specific visual object agnosia, will allow more detailed cross-case comparisons of color recognition disorders.

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Primary diagnosis of interest

Color agnosia

Author's designation of case

JT

Key theoretical issue

- Given intact color discrimination and access to linguistic color terms, how can the analysis of patient errors on color tasks be interpreted within the context of contemporary theories of color cognition?

Key words: color agnosia; error analysis; confrontational naming; multidimensional scaling; associative *vs* visual semantic knowledge; similarity-based representation of visual stimuli

Scan, EEG and related measures

None

Standardized assessment

General: Wechsler Adult Intelligence Scale – Revised (WAIS-R), Annett Handedness Questionnaire
Attention/Memory: Wechsler Memory Scale – Revised (WMS-R)
Language: Controlled Oral Word Association Task, Boston Naming Test, Semantic Fluency
Color Perception: Ishihara plates

Other assessment

Color contrast sensitivity function, color name–abstract concept associations, well-known object–color associations, confrontational color naming, color sorting, matching visually presented colors to auditorily presented color names, coloring line drawings, and choosing the correctly colored object

Lesion location

- Left occipital

Lesion type

Subsequent to a massive intraventricular hemorrhage, an arteriovenous malformation situated at the medial aspect of the occipital horn of the left lateral ventricle was surgically resected

Language

English