

Published in final edited form as:

Cortex. 2014 September ; 58: 217–238. doi:10.1016/j.cortex.2014.05.013.

When concepts lose their color: A case of object color knowledge impairment

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Abstract

Color is important in our daily interactions with objects, and plays a role in both low- and high-level visual processing. Previous neuropsychological studies have shown that color perception and object-color knowledge can doubly dissociate, and that both can dissociate from processing of object form. We present a case study of an individual who displayed an impairment for knowledge of the typical colors of objects, with preserved color perception and color naming. Our case also presented with a pattern of, if anything, worse performance for naming living items compared to nonliving things. The findings of the experimental investigation are evaluated in light of two theories of conceptual organization in the brain: the Sensory Functional Theory and the Domain-Specific Hypothesis. The dissociations observed in this case compel a model in which sensory/motor modality and semantic domain jointly constrain the organization of object knowledge.

1. Introduction

Conceptual knowledge consists of stored information about objects, ideas, and events. Knowing that an elephant is grey, has a trunk, and can be found in Africa is an example of conceptual knowledge. One issue currently debated in the field is the degree to which concept representations are distributed over modality-specific systems, or represented in an amodal or modality-independent format. Another issue that is currently debated is whether or not conceptual knowledge is organized by semantic category. Here we explore the intersection of these two theoretical issues in the context of an individual who exhibited a loss of object-color knowledge across multiple semantic categories.

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Neuropsychological studies of brain damaged patients and functional MRI studies can jointly constrain theories of how concepts are structured in the brain. For instance, patients with naming impairments for animals or for plant life tend to have lesions to the temporal lobe, while patients with disproportionate impairments for artifacts tend to have lesions to parietal-frontal regions (Capitani et al., 2003; Damasio et al., 2004; Gainotti, 2005)—although notable exceptions exist (e.g., Caramazza and Shelton, 1998). Furthermore, areas on the lateral surface of the temporal lobe process object motion (e.g., posterior middle temporal gyrus and the superior temporal sulcus; Beauchamp, Lee, Haxby, and Martin, 2002; Kourtzi and Kanwisher, 2000). Additionally, there are separate pathways in extrastriate cortex for processing form (e.g., lateral occipital cortex) as opposed to other surface properties such as texture and color (e.g., fusiform gyrus; e.g., Cant and Goodale, 2007; Grill-Spector, Kourtzi, & Kanwisher, 2001; see also Cant, Large, McCall, and Goodale, 2008 for behavioral evidence for the independence of form, texture, and color).

Unlike features such as texture, size, and form, color is unique in that it is perceived only through the visual modality. Furthermore, color has been shown to facilitate recognition of natural objects, compared to incorrectly colored or gray-scaled images (Humphrey, Goodale, Jakobsen, & Servos, 1994; for a review, see Tanaka, Weiskopf & Williams, 2001). Recognition of natural scenes is faster for colored as opposed to gray-scaled images (Gegenfurtner and Rieger, 2000). Cant and Goodale (2007) suggested that compared to other surface properties such as texture, object color is analyzed early in visual processing. Others have examined the role of color in higher-level visual areas such as the lingual and fusiform gyrus (for review, see Simmons, Ramjee, Beauchamp, McRae, Martin and Barsalou, 2007).

An important question is whether retrieving object-color knowledge activates the same regions responsible for early color processing. Using positron emission tomography (PET), an early study by Martin, Haxby, Lalonde, Wiggs, and Ungerleider (1995) found that generation of the typical colors associated with objects, when the objects are presented as achromatic line drawings and written words, led to selective activation of a region of the ventral temporal lobe, slightly anterior to the area involved in color perception. However, cortical regions that mediate color perception were not independently defined in that study. Also using PET, Chao and Martin (1999) had subjects passively view colored and gray-scale Mondrian displays, name colored and achromatic objects, and generate colors associated with the achromatic objects. They found that the location of regions activated during color perception (lingual and fusiform gyri) and object-color knowledge retrieval did not directly overlap. Specifically, regions associated with color retrieval were two centimeters lateral to the occipital activations associated with color perception, and were highly similar to the regions involved in simple naming of achromatic objects. This led the authors to conclude that retrieving information about an object's color does not require reactivation of the same areas that mediate color perception. Simmons and colleagues (2007) used fMRI to show overlap in the neural substrate for perceiving color and knowing an object's typical color. They found that a region of the left fusiform gyrus was highly activated for both a color perception task and a color retrieval task that used only linguistic stimuli. This study differed from Chao and Martin (1999) in that all their stimuli were linguistic (i.e., verbal names of objects presented on the screen). The authors interpreted the overlap of regions involved in

color perception and color retrieval as evidence that conceptual knowledge is grounded in modality-specific sub-systems, supporting simulation theories. In addition, they concluded that the posterior lingual gyrus is more active for passive color sensation while the anterior ventral fusiform gyrus involves more active processing of color information for the purpose of extracting meaning (Simmons et al., 2007).

Damage to early visual processing regions can impair the ability to perceive and know about color. Achromatopsia, and impairment for color perception, typically results from lesions to posterior occipital fusiform and lingual gyri (Bouvier & Engel, 2006). Color agnosia is an impairment for knowing an object's prototypical color, due to lesions in ventral temporal cortex (for a review see Simmons et al., 2007). The lesions that lead to color agnosia tend to be slightly more anterior in the ventral visual pathway than the lesions that produce achromatopsia. When selective, these two deficits represent a double dissociation between color perception and color knowledge. Isolated achromatopsia shows that it is possible to have intact color knowledge with impaired color perception (e.g., see Shuren, Brott, Schefft, & Houston, 1996), while isolated color agnosia shows that it is possible to have intact color perception with impaired object-color knowledge (e.g., Miceli et al., 2001; Luzzatti and Davidoff).

Perhaps not surprisingly, cases of impaired knowledge of object color in the context of otherwise spared conceptual knowledge are rare. It is not uncommon to find cases of semantic impairment in which object-color knowledge is impaired along with other stored semantic properties of a category, such as knowledge of an object's function, shape, and texture (e.g., case P.C.O: Miceli, Fouch, Capasso, Shelton, Tomaiuolo, & Caramazza, 2001; see Capitani et al., 2003 for review). Similarly, in cases of semantic dementia, color perception, or the ability to discriminate and categorize colors, is frequently impaired along with object-color knowledge, leading to a general color deficit (Rogers, Patterson, & Graham, 2007). However, selective dissociations have been observed. For instance, case R.S. had impairments for retrieving semantic information about fruits and vegetables, but intact object-color knowledge (in the visual modality) for fruits and vegetables (Samson & Pillon, 2003). Cases G.G. and A.V (Luzzatti and Davidoff, 1994) had intact color perception and impaired object-color knowledge. However, those two cases also had a mild visual form agnosia. The clearest case to date, IOC, was reported by Miceli and colleagues (2001). IOC exhibited color agnosia with normal color perception. Critically, I.O.C. was unimpaired for knowledge of objects' form and function, which at the time made I.O.C. the first (and to our knowledge, only) case on record with a truly selective semantic deficit for object-color knowledge.

Here we report a case (AC) that has a strikingly similar pattern as case I.O.C. (Miceli et al., 2001) as a consequence of a stroke damaging a significant portion of his left temporal and occipital lobes. AC exhibited a semantic impairment for object-color knowledge with spared color perception and spared knowledge of form; in addition, AC's conceptual knowledge of objects was generally spared for both the living and the non-living categories. However, a naming deficit was present for animals, fruit and vegetables, and musical instruments. The aim of this study is to address the issue of how color information is related to other types of information about objects. The observed semantic impairment to knowledge of object color

places new constraints on a model of how object color knowledge is represented alongside other types of perceptual and semantic attributes of objects.

2. Case Report

AC is a 50-year-old right-handed male with 12 years of formal education. In April of 2011, he suffered an intraparenchymal and intraventricular hemorrhage from a ruptured dural arteriovenous fistula (dAVF) in the left occipital lobe. An embolization procedure was performed, and he spent several weeks recovering in the hospital. AC was left with lesions to left dorsal-occipital cortex extending ventrally to include the lingual gyrus, and anteriorly toward the temporal lobe, damaging parts of the medial fusiform gyrus (see Figure 1, Panels A-C). AC's lesion also included bilateral damage to the isthmus of the cingulate gyrus, as well as significant white matter damage. While AC's general language and motor abilities were normal, his peripheral vision and his ability to read were affected by the hemorrhagic stroke. At the first testing session in August of 2011, AC noted that he had been an avid reader before his brain injury, but that since his stroke he had to use a letter-by-letter strategy. This was confirmed with formal testing, in which reading latencies showed a steep slope as a function of word length (372 ms/letter; see Supplemental Materials for details). We did not follow up on AC's pure alexia. Instead, we focused on another area with which he self-reported difficulties—remembering the names and colors of animals as well as vegetables and fruits (see Figure 1, Panel D for his own colored drawings, which point to a clear difficulty with knowledge of the typical color of objects). This latter difficulty was particularly troubling to AC, and interesting at a theoretical level, because his family owned a produce store, and he had been around produce beginning as a child and through the majority of his adult life. The investigation began in August of 2011 and lasted until June of 2013.

Control Participants—Unless otherwise noted, six males served as control participants for comparison of AC's performance. Controls had no history of neurological illness and matched AC for age (mean = 49.3 years; range 42–55 years), education level (mean = 14.9 years; range = 12–18 years), and handedness (Edinburgh Handedness Questionnaire, Oldfield, 1971; mean = .92; range = .53–1; AC's handedness coefficient was 1).

General Methods—For all tasks, unless otherwise noted, AC was instructed to respond quickly and accurately on every trial. Each stimulus was presented on the screen for ten seconds, or until a response was produced, whichever came first. If AC did not produce a response within ten seconds, the trial was counted as incorrect and given a score of zero. All pictorial stimuli were 400 by 400 pixels and gray-scaled, unless otherwise stated (Monitor info: 1680 x 1050 pixels, temporal resolution: 120 Hz, viewing distance: 60 cm). Stimulus presentation for experiments requiring overt verbal responses was controlled with DMDX (Forster & Forster, 2003); the resulting wav files were scored offline by the experimenter. All other experiments were either pen and paper tests or required keyboard presses, and were controlled with E-Prime Software 2.0 (Psychology Software Tools, Pittsburgh, PA; for experimental precedent, including appendices with stimuli names, see Garcea, Dombovy, and Mahon, 2013). Modified t-tests were used to assess if the performance of AC was

different from control participants (Crawford & Garthwaite, 2002) and the Revised Standardized Difference Test (RSDT) was used to test whether the difference between a patient's standardized score on two tasks (X and Y) was significantly different from the differences observed in the control sample (Crawford & Garthwaite, 2005). The results of our experimental investigation are organized by the cognitive processes targeted.

2.1. Study I: Mid-to-High Level Visual Processing

Visual Acuity—AC had self-reported peripheral visual loss as a result of his hemorrhage but reported excellent central visual acuity. An in-house visual field test confirmed that AC had no difficulty identifying briefly presented letters within six degrees of fixation (90/90, duration of stimulus = 130 ms). In addition, AC was successful when reaching and grasping objects within foveal (central) vision. All stimuli (for all tests) were therefore presented within the unaffected portion of his visual fields (central ~8 degrees) and we did not pursue the self-reported peripheral vision loss further.

Motion Perception—AC was asked to decide whether a centrally presented human point-light walker (Johansson, 1973) was walking (in place) in a leftward or rightward direction. The direction in which the point-light walkers were walking varied from 90 degrees from center (left or right) to within 15 degrees of center—randomized on each trial (stimuli obtained from <http://www.biomotionlab.ca/Demos/BMLwalker.html>). AC's ability to discriminate the direction in which the point light walker was walking (forced choice: left/right) was at ceiling. Eighteen months later, AC's perception of animal motion was tested with two sessions of a same/different discrimination task in which an animal comprised of dot configurations was moving in different directions on the screen for an average of 335 ms¹. AC's task was to decide whether the movement of the current stimulus was the same or different as the movement of the preceding stimulus and the condition was randomized. On average, AC successfully discriminated 94% of the trials (33/36 and 35/36 trials on the first and second sessions, respectively, scoring within the range of 3 undergraduate control participants—see Table 1a).

Color Naming—AC was asked to identify the color of a centrally presented colored square. The stimuli consisted of nine colors: red, orange, green, blue, purple, pink, black, gray, and brown. AC completed this task two times – a few months after his stroke and five months post-stroke. AC's performance was within control range when first tested (7/9, controls' range: 7–9), and at ceiling several months later (9/9). The first time, AC missed 2 colors: pink (called it 'purple') and brown (called it 'orange'); those errors were more than likely due to poor saturation of a monitor. Eighteen months later, in June of 2013, AC was given the same task using 11 colors (black and yellow were added); he successfully named 11/11 colors (see Table 1a).

Color-name matching—AC was presented with a color patch (consisting of one of eleven basic colors: red, orange, yellow, green, blue, purple, pink, white, black, gray, brown) and was verbally given three-color names. One option was a color similar to the target color

¹We are grateful to Emily Grossman for making these stimuli available.

(e.g., “red” for target “orange”), another option was a dissimilar color (e.g., “black” for target “orange”) and a third option was the correct color. AC made correct decisions on 11/11 color patches, showing that he had good color perception and understood the verbally presented color names (see Table 1a).

Color Name Categorization—AC was asked to provide a basic color name for each group of color patches grouped according to the same hue. There were eight groups of colors: red, orange, yellow, green, blue, purple, pink and gray; each color group consisted of 6 different hues/shades. AC identified all eight color groups with their correct basic color name (see Table 1a).

Farnsworth and Munsell 16 Hue Task—AC was given several seconds to view the 16 Farnsworth and Munsell color patches in their correct order, and the patches were then scrambled. He was then given two minutes to order the patches into ascending hue. Over two test sessions AC’s performance indicated largely intact color perception: he would occasionally misalign one or two color patches, but successfully ordered the great majority of hues on two separate sessions spaced several months apart. Importantly, his hue categorization was always correct and the few color patches that were misaligned always remained within-hue. AC repeated this task eighteen months later (June 2013) and this time he successfully ordered every patch from 0–15.

AC also completed the online version of the short “Farnsworth D15 arrangement test” (<http://www.color-blindness.com/color-arrangement-test/>). The same instructions were given except that the first color square was provided. AC correctly ordered every color square resulting in a “not colorblind” outcome.

Farnsworth and Munsell 100 Hue Color Vision Test—As a follow-up (June 2013) AC was given the longer online version of the Farnsworth sorting task consisting of 100 patches (<http://www.color-blindness.com/farnsworth-munsell-100-hue-color-vision-test/>). AC’s scored a 104, which is considered slight to moderate colorblind, with his main axis of confusion being red-green. As an immediate follow-up, AC was asked to categorize the sorted patches into basic color names; he accurately named every group of shades.

Ishihara Color Plates—AC was given 12 standard Ishihara plates used to evaluate color blindness, and correctly identified the number in all of the plates (12/12); this was also the case when he was given a follow up color blindness test consisting of plates with geometric shapes (4/4). In a follow-up eighteen months later (June 2013), AC was given 29 standard plates and correctly identified 28/29 (see Table 1a). It is noteworthy that the Ishihara Color Test is most commonly used to diagnose red-green color deficiencies and is a highly sensitive measure of color perception—the dots which form a number or shape are only visible to individuals with normal color vision, and are either invisible or difficult to see, for those with a color deficiency.

Part-Matching Test—On every trial AC and controls were presented with three objects. One object was a target tool or an animal with a portion of the object omitted (stimuli were edited with Adobe Photoshop), and next to the target stimulus were two choices from which

to pick: one object was the correct part missing from the target, the other was a foil that was part of another animal/tool (e.g., target: kangaroo's body; correct match: kangaroo's head; foil: camel's head; for precedent, see the 'heads test' in Caramazza & Shelton, 1998). AC performed at the level of controls on this task (15/16). See Table 1a.

Birmingham Object Recognition Battery—In order to fully assess AC's mid and high visual processing, all subtests of the Birmingham Object Recognition Battery (BORB; Riddoch and Humphreys, 1993) were administered. AC's mid-level vision was within the range of age-matched controls for all of the BORB subtests, with the exception of picture naming (see Table 1b for summary of tests). AC's performance on the short and long versions of the picture naming task were markedly worse than controls (Short: 6/15, controls' range: 8–15, $p < 0.01$; Long: 62/76, controls' range: 64–76, $p < 0.05$). On the short form, AC correctly named 3 out of 9 animals, 1 out of 3 fruit, and 2 out of 3 vegetables. On the long form, AC correctly named 19 out of 27 animals, 5 out of 6 vegetables, 3 out of 4 fruit, 9 out of 12 tools, and 26 out of 27 "other" items. Overall, the errors in picture naming consisted of 6 semantic (and perhaps visual) errors (e.g., dog → 'fox'; cherry → 'plum'), 1 phonological error and 16 omissions (not providing a response within 10 seconds).

Object Decision—In addition to the object decision subtest of the BORB, on which AC was unimpaired (see above), he also completed an extended test with 80 black and white line drawings. Of the 80 stimuli, half were tools and animals, and half were real and not real (for original materials see Barbarotto, Laiacona, Macchi, & Capitani, 2002). In an attempt to titrate the difficulty of the task, the duration that the stimuli were on the screen was varied over testing sessions: Session 1: 10 second duration; Session 2: 1 second; Session 3: 500ms; Session 4: 200ms.

AC was not different than controls when making reality judgments over stimuli presented for 10 seconds (73/80). Although control data were not collected for the 1-second, 500 ms, and 200 ms durations, AC's performance remained above 80% for both living and nonliving stimuli as shown in Table 2.

Visual Episodic Memory—To investigate visual episodic memory, AC was asked to identify repeated images embedded within the presentation of 216 total images (adapted from Brady, Konkle, Alvarez, & Oliva, 2008). His performance on this task was within control range. All methods and results can be found in the Supplemental Online Materials section.

Interim Summary of Study I: Mid-to-High Level Visual Processing—The investigation of mid-to-high level visual processing indicates that while AC had impairments for picture naming (as assessed with the BORB), all other tests were within control range (see Tables 1 and 2 for summary). Of particular importance, AC's color perception was generally spared. Although on the first session of color naming AC was not perfect, his performance was not markedly different than controls. Furthermore, although AC scored in the slight to moderately colorblind range on the full Farnsworth color task, his performance on the Ishihara plates as well as the shorter versions of Farnsworth ruled out any major color blindness. It is also important to note that AC's color categorization was

intact. Knowledge of the correct form of objects was intact in AC as evidenced by his unimpaired performance in object decision. This was the case even when the stimuli were presented on the screen for only 200 ms, and AC's accuracy remained above 80%. Further confirmation that processing of visual form was unimpaired is provided by the part matching task and the visual episodic memory test. Finally, it is important to note that AC does not have difficulty associating color names to color concepts, as for instance evidenced by his intact color naming and intact color-name-to-color matching. This observation is critical in interpreting AC's consistently poor performance (see below) in tasks requiring him to access the color of objects. We next sought to test the integrity of AC's semantic memory for different categories of objects.

2.2. Study II: Conceptual Knowledge of Objects

Snodgrass and Vanderwart Picture Naming—AC named the full set of 260 black and white Snodgrass and Vanderwart (1980) pictures two times, over two separate sessions separated by a month. A third time he named only 80 items matched for linguistic and conceptual factors (following Barbarotto et al., 2002; see Appendices B, C, and D for ratings). His performance on the two full naming sessions was significantly different from controls (336/520, $p < 0.001$). His errors were generally marked by omissions (failing to provide a response within ten seconds; 60%), semantically related errors (e.g., dog → cat; 30%), and visual errors (e.g. lemon → onion; 10%).

Analysis of Snodgrass and Vanderwart by semantic category—In the interest of controlling for nuisance variables that vary across semantic category, a subsequent analysis included only 80 items out of 260 (8 categories ranging from 9 to 11 items in each) for which frequency, familiarity, and visual complexity are matched across category (Barbarotto et al., 2002). Stimulus order at each session was random, and AC was instructed to name the pictures at the basic level name into a microphone. For scoring of accuracy, name agreement values were obtained from Appendix B, Table B1 in Snodgrass & Vanderwart (1980). On the first test session, AC was impaired relative to controls for animals, fruit, vegetables and musical instruments (animals: 2/11, $p < 0.001$; fruit: 5/10, $p < 0.001$; vegetables: 4/10, $p < 0.05$; musical instruments: 5/10, $p < 0.01$).

On the second session, he was impaired relative to controls for animals, fruit, and musical instruments (animals: 6/11, $p < 0.01$; fruit: 6/10, $p < 0.001$; and musical instruments: 4/10, $p < 0.01$). On session 3 AC remained impaired for the same categories as session 2: (animals: 6/11, $p < 0.01$; fruit: 6/10, $p < 0.001$, and musical instruments: (4/10, $p < 0.01$). He remained unimpaired for the categories of body parts, furniture, tools, and vehicles. See Table 3 for accuracy as a function of category, for case AC and controls.

Naming from Definition—AC and control participants were asked to name (at the basic level) 72 auditorily presented definitions. The definitions described features of common objects, which were from the same set of 80 Snodgrass stimuli described above. When collapsing across all categories, AC's performance on this task was significantly different from controls (48/72, controls' range: 59–67, $p < 0.01$). However, inspection of his performance by category revealed that his definition naming was impaired for animals, fruit,

vegetables and musical instruments (animals: 6/9, controls' range: 8–9, $p < 0.01$; fruit: 3/9, controls' range: 6–8, $p < 0.05$; vegetables: 6/10, controls' range: 7–9, $p < 0.05$ and musical instruments: 5/9, controls' range: 7–8, $p < 0.01$). Tools, furniture, and body parts were within control range and vehicles were marginally impaired (6/9, $p = 0.06$). See Table 4 for average performance for each category.

Pyramids and Palm Trees—The word version of the Pyramids and Palm Trees test (PPT; Howard & Patterson, 1992) was administered to AC. A triad of three words was aurally presented for AC to choose which two of three items were most similar. AC's performance was within control range (46/52; see Table 4).

Picture-Word Matching—52 black and white line drawings from the Snodgrass and Vanderwart (1980) corpus were presented one at a time with a word below the picture and AC was asked to decide if the picture and word matched. On 'different' trials, the foil was manipulated such that it was phonologically related (e.g., picture: pear, word: pepper), semantically related (e.g., picture: mouse, word: cat), or unrelated (e.g., picture: lemon, word: vase) to the target picture. There were an equal number of living and non-living items and some pictures appeared multiple times. Words were read aloud by the experimenter along with the presentation of the printed words and pictures, as AC was a letter-by-letter reader (see Supplemental Materials), and we did not want his reading difficulties to contaminate his performance. His performance was within control range when matching aurally presented words with pictures (116/120, 4 semantic errors; see Table 4).

Knowledge of object size—AC and control participants were asked to decide which referent of two visually presented words (i.e., nouns) was larger (e.g., “What is larger, a hammer or a broom?”). Forty-five objects were selected from the Snodgrass and Vanderwart corpus; pairs of objects were either living items, non-living items, or a living item paired with a non-living item. AC was within control range when making object size decisions (43/45; control range: 40–43; see Table 4).

Object Color Naming: Natural and Man-made Items—AC and control participants were asked to name the prototypical color of verbally presented natural (e.g., sun, tree) and man-made objects (e.g., basketball, brick). In comparison to controls, AC was impaired with natural (6/10, control range: 8–10, $p < 0.05$) and manmade items (10/13, control range: 12–13, $p < 0.01$; see Table 4).

Matching Colors to Objects—Thirty black and white target line drawings of common objects from the Snodgrass and Vanderwart corpus were presented with two colored squares to the lower left and right of the target image. On every trial AC and control participants were instructed to select which color best matched the target image. AC completed this task on two separate test sessions separated by two months. AC's performance was impaired, relative to control participants, in Session 1 (22/30, control range: 27–29, $p < 0.01$) and Session 2 (25/30, $p < 0.05$; see Table 4). It is important to note that this task requires only visual input and output (see interim summary for significance of this task).

Inside/Outside Color of Produce—AC and controls were verbally presented with a total of 20 fruits and vegetables. The instructions were to state if the given fruit/vegetable is the same color on the outside as it is on the inside. They were to respond with either “same” or “different.” For example, a watermelon would be considered “different” and an orange would be considered “same.” AC scored at chance on this task (55% accuracy; control average = 83%, standard deviation of controls = 0.1). A Chi-squared analysis confirmed that his performance was not different from chance ($X^2 = 0.8, p = 0.37$).

Semantic Attribute Questionnaire—AC was asked to make property judgments for 20 living (fruits, animals) and 20 non-living (tools, vehicles) concepts. On every trial AC indicated if a visually presented sentence was true or false (e.g., “Is it true that zebras are blue?” “Is it true that cars are used for transportation?”). All true questions were selected from Cree & McRae’s (2003) normative database. Cree & McRae (2003) asked 30 participants to list the most relevant features for each of 540 concepts (e.g., bananas are yellow; hammers are used for pounding nails), and they subsequently ranked which features were most often given for each concept. Here, “true” questions were selected by taking the top ranked object features for the forty concepts; however, not all knowledge types were relevant for each concept. For instance, fruit questions were comprised of visual form, visual color, and taste information, while tool questions were comprised of visual form, encyclopedic and functional information. For each true question, we developed and normed a false question pertaining to the same knowledge type (e.g., “Is it true that bananas are pink?” “Is it true that hammers are used for painting?”). See Supplemental Online Materials for details of the norming.

Overall, AC’s performance was not significantly different from undergraduate students (94%, $t < 1$). Furthermore, when a category analysis was performed, AC was within control range for all four categories (Animals, Tools, Fruit, Vehicles; see Table 5). Importantly, when collapsing across categories and analyzing performance for the ten knowledge types, AC was significantly different than controls only for Visual-Color knowledge (29/36, 81%; control range: 32–36, $p = 0.01$; see Figure 2 for t-scores and Supplemental Table 3 for details). AC was within control range for all other knowledge types. Additional RSDT analyses confirmed that AC was impaired for color knowledge relative to each of the other 9 types of knowledge (See Supplemental Table 2). AC was impaired on color for the category of fruit ($p < 0.001$) with a trend for tools ($p = 0.06$) but not animals, or vehicles. Also note that the only other 2 impairments relative to controls were for animals’ form ($p = 0.04$) and for encyclopedic knowledge of tools ($p = 0.01$; see Supplemental Table 4 for averages for category as a function of knowledge type).

Object Color Naming: Personally Familiar Items—To test whether AC’s impairment for knowledge of object color extended to his personal belongings, we asked him to name the colors of items that he encountered on a daily basis in his house (e.g., “What color are your bed covers?” “What color are your dogs?” “What color is your kitchen table?” Etc.). Questions were created on the same day of testing by asking his wife in a separate room to tell us what things in their house had distinct colors, and what the colors were. Out of 19 questions probing his color knowledge for familiar items, AC correctly answered only 34%

of them. He admitted that he often guessed a random color because he could not remember the correct one.

Interim Summary: Study II: Conceptual Knowledge of Objects—AC's consistently named animals, fruit and vegetables with more difficulty than non-living items such as tools, vehicles, and furniture, suggesting a mild category-specific naming impairment for living items. As has been observed in other cases of differential impairment for living things, musical instruments were also disproportionately impaired (for review and discussion, see Capitani et al., 2003). A slight improvement was observed when tested a few weeks or months after the initial session, but the category effect remained. Furthermore, it is interesting to note that AC had difficulty producing the name of an item from its definition. Table 6 shows RSDT analyses comparing performance between naming living and non-living items (with musical instruments and body parts excluded; see Capitani et al., 2003) and reveals that for both Snodgrass and Vanderwart Picture Naming and Naming from Definition, AC's performance is worse for living items relative to non-living items, referenced to controls (Picture Naming: $p = 0.001$, Naming from Definition: $p = 0.06$). It is important to mention that because *individual* subject naming averages are needed to compute task correlations (and these are not provided for the original 42 controls in Snodgrass and Vanderwart, 1980), for this particular analysis we used control values from 19 healthy undergraduates who came into our lab to name these same 60 pictures.² Crawford's t-tests revealed that even with this control sample, the same categories that were impaired in the patient relative to the 42 original controls remained impaired: animals, fruit, vegetables, and musical instruments. This gave us theoretical motivation to run the additional RSDT analysis confirming that worse performance is observed for living as compared to non-living items in reference to controls.³

Finally, a regression analysis was carried out in which the dependent variable was the mean naming performance, collapsing across session; the predictor variable was a dummy-coded variable coding for category (0 = living; 1 = nonliving). Overall, category membership accounted for 8.7% of the variance in naming performance, which was a significant contribution ($R^2 = .087$; $F(1, 59) = 5.64$, $p < .05$). Living items were named less accurately than nonliving items ($\beta = .30$, $t(59) = 2.38$, $p < .05$). However, when a logistic regression analysis was performed over the naming data (excluding body parts and musical instruments), the living/non-living category effect disappeared when controlling for frequency, familiarity, and visual complexity. Thus, there may not be any particularly strong, if any, category effect (see Capitani et al., 2003). In the General Discussion we return to this issue, and in particular, base the discussion on the generalization that if there is any pattern by category, it is that performance for living items is worse.

The Semantic Attribute Questionnaire revealed that out of ten knowledge types, the only type for which AC was impaired relative to controls was object-color knowledge. Similarly,

²The categories of musical instruments and body parts are excluded in the analyses because in past cases of category-specific deficits, musical instruments tend to pattern with living and body parts with nonliving categories (see Capitani et al., 2003 for discussion and references).

³When body parts and musical instruments *were* included in the analyses, living items were marginally impaired relative to non-living items ($p = 0.07$).

while he was unimpaired for general semantic tasks such as Pyramids and Palm Trees and picture-word matching, he was impaired on the Matching Colors to Objects task, which requires access to the typical color of an object. It is important to note that the impairment in AC for knowledge of object color cannot be explained by a general difficulty with accessing concepts from words, or words from concepts—his performance is intact across a number of tasks requiring the mapping of meaning to words, as long as the task does not require that AC retrieve knowledge of object color. There was no evidence that AC's impairment for knowledge of object color was restricted to fruits, vegetables, and animals – it also extended to nonliving natural items and manmade items, as well as familiar living and nonliving things found in his own house.

2.3. Study III: Targeted investigation of impairment for object-color knowledge

We wanted to more fully characterize the extent to which AC's object-color knowledge was impaired using a common set of items across tasks. The goal of Study III was to use the same set of items (Snodgrass and Vanderwart pictures with prototypical colors) and query multiple types of information about them in order to ensure that the principal dissociations could be observed entirely within items.

Object Color Naming for Snodgrass and Vanderwart Pictures—On every trial, AC and control participants were instructed to name the prototypical color of black and white Snodgrass and Vanderwart pictures ($N = 108$). AC completed this task twice, with three months separating the two sessions. On the first test session, AC was impaired for animals (36/54, controls' range: 44–49, $p < 0.05$), fruit (5/12, controls' range: 9–11, $p < 0.01$), tools (9/19, controls' range: 17–19, $p < 0.001$), and vegetables (8/12, controls' range: 11–12, $p < 0.01$). When given the same task several months later, AC's performance remained impaired for vegetables ($p < 0.01$) and fruits ($p = 0.05$), while his object-color naming for animals ($p = 0.06$) was only marginally impaired. It is notable that AC's color naming for vehicles was at ceiling. Furthermore there was a dramatic improvement for naming colors of tools, which may be partly attributed to practice effects (and the more 'generic' responses that are required for artefacts, such as 'silver'). See Table 7 and Figure 3 for accuracy as a function of category.

Categorizing and defining objects—Concepts from the Snodgrass and Vanderwart picture set ($n = 108$) were verbally presented for AC and three naïve controls to categorize (at the superordinate level, e.g., animal, food, tool, vehicle) and then describe. Participants were instructed, when defining the concepts, to provide specific information about object properties (e.g., form, color, function, if the object is edible, environment where the object exists, if the object is dangerous, etc.). AC's verbal responses were recorded, and scored offline. AC was at ceiling when categorizing (108/108), and his definitions of the items (across all categories) were generally accurate. However, when color information was included in his definition, it was often incorrect. For instance, when asked to define a peacock, AC responded with "...known for display of color with their feathers, *red*, *black*, two legs, they fly and walk, and probably swim too." He defined a carrot as a "*green* skinned, *white* inside, edible vegetable, you use it with lots of different types of cooking."

To objectively score the appropriateness and completeness of AC's definitions in comparison to healthy controls, three undergraduate students naïve to the purpose of the study were instructed to rate AC's responses for each knowledge type for each category using "0" or "1" (for animals, fruit, vegetables, tools, and vehicles). Similarly, two other naïve individuals were asked to rate each of the three control subjects' definitions with the same binary scale (two raters per control, total of six raters). These ratings were averaged to obtain a final average for each knowledge type of each category for both patient and controls.

For the category of animals, color information was the only knowledge type that was marginally significant when comparing the patients' scores to the controls' scores ($p = 0.067$). For fruit, color information was impaired in AC relative to controls ($p = 0.03$), along with texture ($p = 0.04$) and size ($p = 0.01$). For vegetables, color was the only type of knowledge significantly different ($p = 0.04$). For tools, no knowledge type was impaired and for vehicles, only color was marginally different ($p = 0.05$). See Table 8 for comparisons of all categories and knowledge types.

Follow-up RSDT analyses were completed comparing color information to all other types of information within category. These analyses were theoretically driven since the patient had the lowest averages for color as confirmed by the t-tests performed above. For animals, color was impaired relative to animals' climate ($p < 0.05$), whether it was dangerous/friendly ($p < 0.01$), and typical foods eaten (e.g., herbivore or carnivore; $p < 0.01$). AC's color knowledge of animals was not impaired relative to knowledge of the number of legs, size, and typical motion associated with animals (all $p > .05$). For fruit, color was impaired relative to all other knowledge types, e.g., where fruit is grown ($p < 0.01$), taste ($p < 0.001$), function ($p < 0.001$), texture ($p < 0.001$), size ($p < 0.001$), shape ($p < 0.01$), and seeds/pits ($p < 0.05$). For vegetables, color was impaired relative to taste ($p < 0.01$), function ($p < 0.01$) and texture ($p < 0.05$), but not to where they grow, size, shape, or seeds. For tools, color was impaired relative to shape ($p < 0.05$) and size ($p < 0.01$), but not function. Finally for vehicles, color was impaired relative to all knowledge types: function ($p < 0.001$), size ($p < 0.001$), shape, ($p < 0.001$) and mode of transport (see Supplemental Online Table 5 for all comparisons and means).

Interim Summary: Targeted investigation of impairment for object-color knowledge—Findings from the Object Color Naming task and the Categorizing and Defining task suggest that AC was impaired for knowledge of the prototypical colors of items. It is of some importance to note that over time AC showed modest improvement in naming and retrieving the color of nonliving items such as tools and vehicles. A similar conclusion is also supported by the results of the Categorizing and Defining Task: when asked to come up with descriptions of various features of living and non-living items, AC's definitions were accurate and comprehensible. The only parts of the descriptions that were incorrect concerned items' color.

2.4. Study IV: Modality-specificity of the object-color knowledge impairment

We developed several tasks that manipulated the format of input (e.g., visually presented pictures; auditorily presented words) to see if the color knowledge impairment was present regardless of the format of the input. Over three tasks AC and control participants were asked to match seventy-eight living items with their prototypical colors; the stimuli consisted of verbal names or colored and black and white images of animals, vegetables, and fruit from the Snodgrass and Vanderwart corpus (for precedent, see Miceli et al., 2001).

Generation of the typical colors of objects—On every trial the experimenter verbally presented an item (e.g., “frog”) and AC and control participants were instructed to verbally produce the canonical color of the item. Colors were defined as “canonical” based on responses of 5 independent undergraduate judges (i.e., if 3 of the 5 judges listed a frog’s canonical color as ‘green’); AC’s performance was contrasted against control participants for items that were objectively canonical. Collapsing across categories, AC was significantly different than control participants (54/78, controls’ range: 70–77, $p < 0.01$). The analysis of performance by category revealed that AC was impaired for all three categories (Animals: 37/54, control range: 44 – 51, $p < 0.05$; Fruit: 8/12, control range: 10–12, $p < 0.05$; Vegetables: 9/12, control range, 11–12, $p < 0.01$). Errors were either incorrect colors or omissions (see Table 9).

Visual-Visual Object Color Matching—AC and control participants were presented with three horizontally aligned colored drawings of the same object on every trial, and were instructed to select the object that was correctly colored (e.g., celery colored green); the objects’ colors were systematically manipulated such that there was a “hard” foil (e.g., celery colored yellow) and a “easy” foil (e.g., celery colored blue) on every trial. Across all categories, AC was marginally impaired relative to control participants (63/76, controls’ range: 69–73, $p = 0.05$). While his performance matching object colors for animals was mildly impaired (39/52, control range: 41–47, $p = 0.05$), his performance for vegetables (11/12) and fruit (10/12) was not different than controls. Of the 13 errors, 10 were committed on “hard” foils, and 3 were committed on “easy” foils.

Eighteen months later (June, 2013) AC completed the same task, and was more impaired than previously, with respect to control performance: AC was impaired collapsing across categories ($p < 0.05$), and showed impairments for animals ($p < 0.01$) and vegetables ($p < 0.01$), but not for fruit ($p = 0.8$; see Table 9).

Visual-Verbal Object Color Matching—On every trial three verbally presented colors were paired with a visually presented black and white line drawing, and AC and control participants were instructed to select the correct color that matched the visually presented object. The same object-color pairings were used as in the *Visual-Visual Object Color Matching* task. AC was impaired when making visual-verbal object color decisions (51/76, controls’ range: 69–74, $p < 0.001$). AC was impaired for animals (37/52, control range: 42 – 48, $p < 0.05$) fruit (7/12, control range: 11–12, $p < 0.001$) and vegetables (7/12, control range: 11–12, $p < 0.001$). Of the 25 errors committed, 7 were committed on “hard” foils, 5 on “easy” foils, and 13 were omissions (see Table 9).

Interim Summary of Study IV: Modality-specificity of the object-color

knowledge impairment—The tests in this section demonstrated that AC's impairment for object-color knowledge extends to the visual and verbal modalities. On some tasks, knowledge of animals' color was specifically impaired than that of fruit and vegetables, while on other tests he was impaired for all categories. An appreciable pattern is that on the first session, AC performed better in the visual-visual color matching task than the verbal-visual matching task, and his impairment was differentially expressed for animals compared to fruit and vegetables. However, when tested eighteen months later, he was impaired for both animals and vegetables, demonstrating that i) his object-color knowledge impairment persisted two years after his stroke, and ii) his impairment remained modality-independent. Follow-up RSDT analyses found that when the three modality tasks were paired with each other, the only significant difference in comparison to controls was between the Visual-Visual and Visual-Verbal tasks, with worse performance for Visual-Verbal relative to Visual-Visual ($p < 0.05$). RSDT also confirmed that there was no category effect for animals versus plant life.

2.5. Study V: An implicit test of AC's object-color knowledge impairment

In the Stroop paradigm, participants are slower to name the ink color (e.g., blue) of a printed incongruent color-word (e.g., red) compared to a printed congruent color-word (e.g., blue; Stroop, 1935; Dalrymple-Alford, 1972; for reviews, see MacLeod, 1991; Roelofs, 1993). Another finding is that participants are faster to name the ink color (e.g., blue) of a congruent noncolor-word (e.g., ocean) compared to an incongruent noncolor-word (e.g., dollar; Dalrymple-Alford, 1972; for a recent replication, see Mahon, Garcea, and Navarrete, 2012). The combination of those two experimental manipulations offers an ideal means for demonstrating, with the implicit measure of response time, the dissociation between intact color naming, and impaired object-color knowledge. We thus asked AC to name target ink colors (e.g., blue) while ignoring superimposed distractors that could be: **i**) congruent (e.g., ocean) and incongruent (e.g., dollar) non-color words, and **ii**) congruent (i.e., blue) and incongruent (e.g., pink) color words (see Figure 4 for conditions and stimuli). We predict that **i**) AC would not show the typical pattern for non-color words, but **ii**) would show a typical Stroop effect (control data and all details of the design and procedure come from Mahon et al., 2012).

Stroop Paradigm Analysis—AC's response time data were entered into an ANOVA with two factors 'color-word distractor status' (levels: color-word, noncolor-word) and 'congruency' (levels: congruent, incongruent). There was a main effect of color-word distractor status $F(1,12) = 11.33$, $MSE = 2276.6$, $p < .01$, no main effect of congruency $F(1,12) = 2.66$, $MSE = 1513.2$, $p = .13$, and an interaction between color-word distractor status and congruency $F(1,12) = 12.92$, $MSE = 810.97$, $p < .01$. Planned comparisons (t-tests, two-tailed) compared the congruent and incongruent conditions for color word and non-color word distractors, separately. Consistent with our expectations, for color word distractors, AC's naming latencies were slower for incongruent distractors than congruent distractors ($t(12) = -6.34$, $p < .001$; mean difference, 46 ms, SD, 26 ms), while there was no difference for non-color word distractors between congruent and incongruent distractors ($t < 1$; mean difference, 11 ms, SD, 63 ms). Controls showed both effects (control data from

Mahon et al., 2012)—that is, an effect for both color-word and non-color-word distractors. Figure 5 plots the magnitude of the response time differences between the congruent and incongruent conditions for the color-word and noncolor-word conditions, separately, for both AC and controls.

One concern that could be raised with the observed null finding for the noncolor-word distractors is that AC is not able to process those printed distractor words (for whatever reason). This can be controlled by embedding the same distractor words in an object-naming task. The picture-word interference paradigm is a close analogue to the classic Stroop task, in which participants name pictures of objects while ignoring superimposed distractor words. It is known that participants are slower to name pictures of objects in the context of semantic category coordinate distractors compared to unrelated distractors (e.g., see Glaser and Dungenhoff, 1984; Lupker, 1979; Mahon et al., 2007; Rosinski 1977; Schriefers et al., 1990; Vigliocco et al., 2004).

We thus set out to investigate if the items (distractor words) that did not affect ink naming latencies would affect picture naming latencies. If AC's locus of impairment is restricted to object-color knowledge, and not to object- or color- knowledge per se, then his performance in the picture-word paradigm using the same noncolor-word distractor words, should resemble the "normal" profile of performance (e.g., semantically related distractors will interfere more than semantically unrelated distractors).

Picture-Word Interference Design and Analysis—On every trial AC was presented with a (target) picture and a superimposed distractor word, and was instructed to name the target quickly and accurately. The distractor words were the non-color words from the Stroop task (fire, ocean, dollar, eggplant, ham), and the target pictures (lightning, river, quarter, lettuce, steak) were semantically related to the distractor words. A within-items design was used such that the same distractor words were repeated with the pictures to produce the unrelated condition. For instance, when naming the target 'steak', the semantically related distractor was 'ham', and the semantically unrelated distractor was 'fire'.

As predicted, AC's naming latencies were 20 ms slower in the related than in the unrelated condition (Figure 5). While the difference is not statistically significant because of low power, both the direction and magnitude of the effect are in line with a number of previous investigations (for review, see Mahon et al., 2007; Spalek, Damian, and Bölte, 2013).

Interim Summary Study V: An implicit test of AC's object-color knowledge impairment—In the classic color-word Stroop paradigm, AC showed the same pattern as healthy participants – slower ink naming latencies for incongruent compared to congruent color names. However, unlike healthy controls, AC did not show any modulation of ink naming latencies when the distractors were color congruent or incongruent but were not color-words (e.g., ocean, blue). In other words, when the congruency was defined by color information that had to be retrieved from an object concept, no effect was observed. However, using the same distractors that produced no effect with ink color naming, AC did show semantic interference in object naming, ruling out any concerns that the patient may

not have been able to process those distractor words. These data show, with an entirely implicit measure, that AC's impairment spares object knowledge and spares color knowledge, and selectively affects object-color knowledge.

3. General Discussion

We have reported a patient who presented with an impairment for knowledge of the typical colors of objects, with relatively intact ability to perceive and name colors (see Tables 1a and 1b for summary of intact mid to high-level visual processing). He exhibited worse naming of animals, fruits, and vegetables compared to tools, vehicles, and furniture, suggesting a category-specific impairment for naming living items. The same naming impairment was evident in naming from definition, indicating that it is unlikely to derive from an agnosia. However, it should be noted that part, or all, of this category effect may be due to stimulus factors such as frequency, familiarity and visual complexity that vary by category—thus restricting the inferences that may be derived from those data. Critically, AC was unimpaired in object decision, with performance remaining at 80% correct even for degraded (200 ms duration) stimuli. His general semantic memory, as measured by tasks assessing conceptual knowledge of object form, function and typical environment or context, was largely spared for all semantic categories. This is important because AC's object color knowledge impairment cannot be explained by an inability to map words to their meanings. AC performs well on tasks that require an ability to map words to concepts when the task does not require *object-color knowledge*. However when asked about object-color knowledge, AC struggles with this particular domain (see Figure 6). Furthermore, he does poorly on object color knowledge tasks that do not have any verbal input and are strictly picture tasks (see Figure 6). AC's language abilities were normal and word reading was the only documented impairment – alexia without agraphia for words but not for numbers. Thus, AC's main impairments to be discussed are the loss of object-color knowledge in the context of a trend toward a disproportionate impairment for naming living items. We argue that the findings obtained with case AC, together with previous work, indicate a model in which both sensory modality and object domain jointly constrain the organization of conceptual knowledge.

3.1. The role of familiarity in shaping semantic deficits

AC's category-specific naming deficit can also be viewed through the lens of the possible contribution of experience-dependent and gender factors in shaping how knowledge is organized. Previous work has shown gender modulation of category naming, with females better at naming living items and males better at non-living, both in individuals with Alzheimer's Disease as well as in healthy subjects (Laiacina, Barbarotto, & Capitani, 1998; Laiacina & Capitani, 2001; McKenna & Parry, 1994). Laws (1999) found that males were in fact faster to name nonliving things while females were faster to name living things. However, Gainotti (2005) found that gender did not influence the living versus nonliving distinction but rather had a strong differential influence *within* the living category—men were more impaired for plant life, while women were more impaired for the animal category. It is also interesting to note here that all cases of category-specific semantic deficits for fruit and vegetables as summarized by Capitani and colleagues (2003) were men.

Those findings, collectively, indicate an important contribution of gender, and suggest that as different types of experiences can be correlated with gender, interactions between such experience-dependent factors, category, and gender may emerge.

AC's pattern of performance disrupts the association Gainotti (2005) was suggesting between category-specific deficits and gender. Based on the gender effect, it would be expected that AC's lowest naming average would be for plant life, but in fact his naming average for animals was lowest. It is also important to point out that AC was an expert in produce his whole life – he worked for a family produce company for many years. Thus, his impaired naming of fruits and vegetables cannot be attributed to poor premorbid knowledge of produce. For example, Jefferies, Rogers, & Lambon Ralph (2011) presented cases of semantic dementia in which individuals who were experts in a certain category (i.e. a car mechanic or a florist) had a selective sparing of knowledge for those respective categories, while semantic knowledge for all other categories was impaired. It is also noteworthy that even though fruits and vegetables are items that are most familiar to AC, his color knowledge and naming were most impaired for those categories. On the other hand, it might be argued that his extensive premorbid expertise could partly explain why fruits and vegetables were not as impaired 'as they should be' given his color knowledge impairment. An interesting issue to explore in future research is how expertise in a given category affects naming and semantic knowledge for that category after brain damage.

3.2. Clues from Case AC about the representation of object color knowledge

The central idea of the simulation or 'embodied cognition' framework is that sensorimotor representations are re-activated or 'simulated' in the course of conceptual analysis, and that sensorimotor activation is therefore a necessary and intermediary step in the computation of meaning (see Allport, 1985 for an early articulation of this view; for discussion and related proposals, see Barsalou, 1999; Gallese & Lakoff, 2005; Glenberg & Kaschak, 2002; Martin et al., 2000; Meteyard et al., 2012; Thompson-Schill, 2003; Zwaan, 2004). As discussed in the Introduction, with respect to object-color knowledge, it has been shown that there is partial overlap in the neural substrates supporting color perception and the retrieval of object-color knowledge (Simmons et al., 2007). However, neuropsychological findings indicate that color perception and object-color knowledge doubly dissociate (Luzzatti & Davidoff, 1994; Miceli et al., 2001, and the data reported herein), and suggest that the overlap in the Simmons and colleagues study is caused by 'higher-level' areas being activated during perception, rather than 'lower-level' areas being activated during color knowledge retrieval.

In an fMRI study, Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill (2011) found that retrieval of object-color knowledge was influenced by both context (type of task) and individual differences (cognitive style). Specifically, when the color retrieval task was verbal and required highly detailed retrieval of color information, the left fusiform was more activated compared to a less-detailed color knowledge task. When looking at cognitive style preferences, the amplitude of the BOLD response in the left lingual gyrus correlated with a preference for a visual cognitive style versus a verbal one. They concluded that neural overlap between these two regions is influenced by such factors and that sensorimotor

theories must be modified to take these variables into account (see also Hsu, Frankland and Thompson-Schill, 2012).

3.3. Clues from Case AC about the organization of conceptual knowledge

One of the most widely discussed theories of the organization of concepts is the Sensory/Functional Theory (SFT). The original formulation of the SFT proposed that: **i)** the semantic system is organized into visual/perceptual and functional/associative stores, and that **ii)** the visual/perceptual semantic subsystem is particularly important for recognizing living things whereas the functional/associative system is important for recognizing non-living things (e.g., Humphreys & Forde, 2001; Warrington & McCarthy, 1983; Warrington & Shallice, 1984; Warrington & McCarthy, 1987). The SFT has also been reformulated at a fine-grained level, distinguishing visual-semantic knowledge for color from visual-semantic knowledge for form, thus allowing the theory to explain fine-grained category-specific impairments that have been observed. For example, patient K.C. (Blundo, Ricci, & Miller, 2006) had a disproportionate impairment for the category of animals, but not for fruit or vegetables (see also Caramazza and Shelton, 1998). Furthermore, Crutch and Warrington (2003), Hart, Berndt, and Caramazza, (1985), and Samson and Pillon (2003) reported patients with selective semantic impairments for fruit and vegetable knowledge. Such fine-grained impairments were problematic for the original formulation of the SFT that maintained that all living things (fruit/vegetables *and* animals) differentially depended on the same visual-semantic sub-system (for arguments, see e.g., Capitani et al., 2003; Caramazza and Shelton, 1998). Thus, the core assumption of recent formulations of the Sensory/Functional Theory (e.g., Cree and MacRae, 2003; Crutch and Warrington, 2003) is that within broadly defined modality-specific systems, more fine-grained processing channels are specialized for (e.g.) color, motion, and form. On this account, color knowledge is more important for distinguishing fruit and vegetables and biological motion and form are more important for recognizing and distinguishing animals (Cree & MacRae, 2003; Crutch and Warrington, 2003; Humphreys & Forde, 2001; Warrington & McCarthy, 1987). Another version of this account explains a category-specific impairment for living items as arising from a modality-specific, rather than a semantic impairment, in the visual domain (Gaffan and Heywood, 1993). It argues that this is due to the fact that living items have more visual similarity to each other than non-living items (see also Humphreys and Forde, 2001; for alternate view see Laws et al., 2002).

An important testing ground for the Sensory/Functional Theory are cases of category-specific impairments. The revised SFT explains category-specific semantic deficits for fruit and vegetables as resulting from damage to object-color knowledge. Likewise, a category-specific impairment for animals is argued to result from damage to the biological motion and/or the form store⁴. One piece of empirical evidence that substantially weakens an explanation of category-specific semantic deficits in terms of dissociations among fine-grained modality-specific channels is the failure to observe a consistent association between category-specific semantic deficits and impairments for the type or modality of knowledge on which the impaired category putatively depends. For instance, several case studies reporting fine-grained category-specific semantic deficits failed to observe the predicted association (e.g., Blundo et al., 2006 ; Crutch & Warrington, 2003; Samson & Pillon, 2003).

Some versions of the SFT offer explanations for the fact that impaired functional knowledge can be found alongside impaired knowledge of living items. For instance, Farah and McClelland (1991) argued that visual knowledge is obligatory when retrieving any information (including non-visual), about living items (see also Thompson-Schill, Aguirre, Desposito, & Farah, 1999). As support for this theory, Thompson-Schill and colleagues (1999) used a functional neuroimaging study to show that for the category of living things, there were no differences in activation in the left fusiform gyrus, hypothesized to support visual semantic retrieval, for visual versus non-visual knowledge retrieval. On that basis, they suggest that conceptual knowledge is organized by anatomically dissociable, but highly interactive, modality-specific sub-regions.

It is thus worth considering how different versions of the Sensory/Functional theory could account for the pattern of impairments observed in our case, as the conjunction of a disproportionate impairment for living items and an impairment for knowledge of object color would seem, at least at first glance, to be exactly the type of association predicted by the SFT, as well as most sensorimotor-type theories.

3.4. Evaluation of a Sensory/Functional account of case AC

An important aspect of AC's profile is relatively intact, if not normal, knowledge of object-form, object-size, and biological motion. The summary graph in Figure 7 shows that a dissociation is present between knowledge types: AC's performance on object-form (the 10 second version of Object Decision) and biological motion perception (Point Light Walker and Animal Motion) were normal ($p > 0.05$), while object-color knowledge (all object-color knowledge tasks averaged together⁵) was impaired relative to controls ($p < 0.01$). The graph also depicts his picture naming performance for all three sessions, broken down by category. A notable pattern is that his average naming performance for animals is, if anything, lower than his performance for fruit and vegetables, although both are impaired relative to controls (animals: $p < 0.001$; fruit and vegetables: $p < 0.05$). Additionally, performance was worse for object-color knowledge compared to object-motion ($p < 0.01$), and performance was worse for object-color compared to object-form, referenced to controls ($p < 0.05$). In other words, since AC's object-color knowledge store is disproportionately damaged, then following SFT's assumptions, his naming performance for fruit and vegetables should be the most impaired—contrary to the data (for a similar argument, see Miceli et al., 2001).

In a further attempt to evaluate the SFT as an explanation of the category-specific impairment observed in AC, we took advantage of the fact that he had been tested on multiple sessions for naming and color knowledge of the same set of concepts. Specifically,

⁴Recent norming studies (e.g., Cree and MacRae, 2003; Vinson, Vigliocco, Cappa, & Siri, 2003) have sought to provide new evidence in support of the idea that fine-grained semantic categories are in fact tied to fine-grained distinctions in knowledge types (e.g., fruit/vegetables → color; animals → motion/form). Those normative studies provide clear evidence that different knowledge types (e.g., color) are differentially important for distinguishing items from a given category (fruit/vegetables) from items from another category. However, the nature of the impairment that is observed in patients with category-specific impairments is not a failure to categorize at the superordinate level, but rather to distinguish items *within* a given category (for discussion see Mahon and Caramazza, 2009). Thus, one might question whether those normative studies in fact provide support for the assumptions of the SFT - that discrimination of items within different categories depends on different types of knowledge.

⁵Matching Colors to Objects (2 sessions), Object Color Naming for Snodgrass and Vanderwart Pictures, Generation of the Typical Color of Objects, Visual-Visual Object Color Matching, Visual-Verbal Object Color Matching, and Color of Natural and Man-made Items.

he was asked to both name and generate the prototypical color of black and white Snodgrass and Vanderwart pictures. This permitted us to test whether AC's ability to name an item would predict his knowledge of that item's color, and vice-versa.

To carry out this analysis, the items were separated according to AC's naming performance (correct or incorrect) in session 1. We then calculated both naming performance and color knowledge, over the same items in session 2, separately for those items that were named correctly at session 1 and those items that were named incorrectly at session 1. The same analysis was carried out separating items according to whether the correct color was retrieved in session 1 (then calculating performance in session 2 for naming and color knowledge). Finally, the analysis was 'jackknifed' such that the data from session 2 were used to separate the items (for both naming, and color knowledge), and percent correct for naming and color knowledge was then calculated over the data from session 1.

The results of that analysis are presented in Figure 8. The bars on the left panel of the figure represent data binned according to being correct/incorrect for color knowledge, and on the right panel, the data represent performance when binned according to correct/incorrect naming performance. In order to compare two proportions, we computed a z-score by dividing the mean difference between two proportions by the estimate of the pooled variance associated with the two proportions; p-values were derived from a standard distribution function with a mean of 0 and a standard deviation of 1. The first pattern to appreciate is that the analysis has power to detect effects. This is demonstrated by the fact that the probability of naming an item correctly in a given session is higher if AC named that item correctly in the other testing session ($Z = 2.85, p < 0.01$). The same pattern obtains for color knowledge: the probability of retrieving the correct color knowledge is higher if AC (in the other testing session) retrieved the correct color ($Z = 7.57, p < 0.001$). This finding indicates that there is consistency in AC's performance, on a session-to-session basis, *within* a given task. However, and critically, the ability to retrieve the correct color in one session did not predict naming performance in the other session, nor did the ability to correctly name an item predict the ability to retrieve the correct color information about that item. As can be seen in the left panel of Figure 8, AC's naming accuracy did not significantly vary as a function of correct/incorrect color knowledge retrieval ($Z < 1$), and as can be seen in the right panel of Figure 8, AC's retrieval of color knowledge was unaffected by his ability to retrieve the name of concepts ($Z < 1$).

These data indicate that variability in performance in the color knowledge test did not relate to variability in naming performance—that is to say, there was no systematic relationship between AC's ability to identify the correct color of an object that he could name and an object that he could not name. These data are problematic for an explanation his poor naming performance in terms of damage to the 'type' or 'modality' of knowledge upon which correct naming (putatively) depends.

3.5. The distributed domain-specific hypothesis

According to the domain-specific hypothesis the first-order organizational constraint on object knowledge is semantic domain. The domain-specific hypothesis, unadorned, cannot explain a selective loss of object-color knowledge. This, and other considerations have

motivated the view (Mahon and Caramazza, 2009, 2011) that modality and domain may jointly constrain the organization of conceptual knowledge – the “Distributed Domain-Specific Hypothesis.”

There are a number of different possible architectures whereby modality-specific and domain-specific constraints could jointly constrain the organization of knowledge, and it is not possible at present to distinguish among them (for precedent see Coltheart et al., 1998; Gainotti & Silveri, 1996; Miceli et al., 2001; Powell & Davidoff, 1995; Samson et al., 1998). One possible architecture is schematized in Figure 9a. According to this model, domain and modality are conceived of as truly orthogonal dimensions of organization. This schematic illustrates how information within a domain can dissociate and be damaged separately from other domains, as well as how information of a given type or modality could be selectively damaged. Another possible architecture is shown in Figure 9b. In this model, modality-specific subsystems are not distributed within domains, but rather are located in separate stores, but with domain-specific connections.

A key issue that is framed by this case report is whether damage to a particular type of information that results from a focal brain lesion propagates to other types of knowledge about the same domain. In other words, is knowledge that is represented by physiologically healthy brain tissue but which is functionally related to compromised information itself compromised or is it insulated from such ‘cascading’ impairment? Price, Warburton, Moore, Frackowiak, & Friston, 2001 (see also Friston and Price, 2001) developed the notion of ‘dynamic diaschisis’ to explain the potential repercussive effects of damaging an aspect of a functional network (see also Feeney and Baron, 1986). Dynamic diaschisis could be a relevant construct for understanding the causes of some selective semantic deficits: Why is it the case that patients with category-specific semantic deficits typically have impairments for all types or modalities of knowledge about the impaired category (Capitani et al., 2003)? And, how is it that some types of modality-specific impairments can be selective to a given class of items (e.g., prosopagnosia) whereas other modality-specific impairments seem to cut across domains, such as a domain-general color agnosia as we have reported here? One recent proposal (Mahon, in press) is that category-specific impairments may arise because damage to one node within a domain-specific network disrupts anatomically intact but functionally coupled regions within a broader domain-specific network.

The schematic models in Figure 9 illustrate how modality specific subsystems can be damaged independently of each other. Patients with isolated form agnosia and those with a selective impairment for object-color knowledge are easily explained on such a model. Such a model could also explain case I.O.C (Miceli et al., 2001) and our current case, by assuming a disconnection deficit. As for case IOC, the case we have reported had difficulties retrieving the typical color of objects, and the difficulty extended to multiple domains (i.e., not just fruit and vegetables). Both schematics (Figure 9a and 9b) represent the idea that different types or modalities of knowledge may be differentially relevant for different domains, although, as we hope to convey, more empirical work is necessary to adjudicate between them. The more general point is that, except for very limited exceptions, visual form is both necessary and sufficient for recognizing an object whereas color by itself is neither. Color knowledge may be called upon more in making fine-grained discriminations

for fruit/vegetables than for tools. Clearly, for some discriminations, such as saying ‘broccoli’ vs. ‘cauliflower’ or ‘lime’ vs. ‘lemon’ color may be the critical and distinguishing feature. For other discriminations, however, color may be far less relevant (e.g., ‘broccoli’ vs. ‘cucumber’). Thus, it may be useful to think of the relevance of different knowledge types as forming a hierarchy, where color information may become relevant very early (broad superordinate level—broccoli versus dog) and then again very late in the process if form information is not sufficient to decisively identify a stimulus (broccoli versus cauliflower). However, other cues such as motion, form, and context are also surely critical, in particular at the broadest level of categorization (e.g., broccoli versus dog).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors are grateful to case AC and his wife for their jovial participation and patience over many hours of testing, Cathy Sweet for help with recruitment, EG Gaffin-Cahn for help with programming, and Emily Grossman for making testing materials available. The authors are also grateful to Eric Hintz for discussing the clinical profile of the patient and to Alfonso Caramazza, Duje Tadin, and Charles Duffy for comments on an earlier draft of this ms. This research was supported by NIH grant R21 NS076176 to BZM.

References

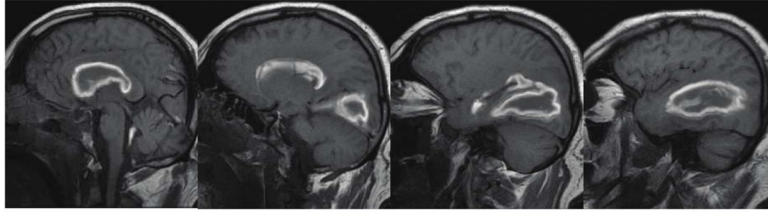
- Allport, DA. Distributed memory, modular subsystems, and dysphasia. In: Newman, SK.; Epstein, R., editors. *Current perspectives in dysphasia*. Edinburgh: Churchill Livingstone; 1985. p. 207-244.
- Barbarotto R, Laiacona M, Macchi V, Capitani E. Picture reality decision, semantic categories and gender: A new set of pictures, with norms and an experimental study. *Neuropsychologia*. 2002; 40:1637–1653. [PubMed: 11992652]
- Barsalou LW. Perceptual symbol systems. *Behavioral and Brain Sciences*. 1999; 22:557–660.
- Beauchamp MS, Lee KE, Haxby JV, Martin A. Parallel visual motion processing streams for manipulable objects and human movements. *Neuron*. 2002; 34:149–159. [PubMed: 11931749]
- Blundo C, Ricci M, Miller L. Category-specific knowledge deficit for animals in a patient with herpes simplex encephalitis. *Cognitive Neuropsychology*. 2006; 23:1248–1268. [PubMed: 21049377]
- Bouvier SE, Engel SA. Behavioral deficits and cortical damage loci in cerebral achromatopsia. *Cerebral Cortex*. 2006; 16:183–191. [PubMed: 15858161]
- Brady TF, Konkle T, Alvarez GA, Oliva A. Visual long term memory has a massive storage capacity for object details. *PNAS*. 2008; 105:14325–14329. [PubMed: 18787113]
- Cant JS, Goodale MA. Attention to form or surface properties modulates different regions of human occipitotemporal cortex. *Cerebral Cortex*. 2007; 17:713–731. [PubMed: 16648452]
- Cant JS, Large ME, McCall L, Goodale MA. Independent processing of form, colour, and texture in object perception. *Perception*. 2008; 37:57–78. [PubMed: 18399248]
- Capitani E, Laiacona M, Mahon B, Caramazza A. What are the facts of semantic category specific deficits? A critical review of the clinical evidence. *Cognitive Neuropsychology*. 2003; 20:213–261. [PubMed: 20957571]
- Caramazza A, Shelton JR. Domain-specific knowledge systems in the brain: The animate-inanimate distinction. *Journal of Cognitive Neuroscience*. 1998; 10:1–34. [PubMed: 9526080]
- Chao LL, Martin A. Cortical regions associated with perceiving, naming, and knowing about colors. *Journal of Cognitive Neuroscience*. 1999; 11:25–35. [PubMed: 9950712]
- Coltheart M, Inglis L, Cupples L, Michie P, Bates A, Budd B. A semantic subsystem of visual attributes. *Neurocase*. 1998; 4:353–70.

- Crawford JR, Garthwaite PH. Investigation of the single case in neuropsychology: confidence limits on the abnormality of test scores and test score differences. *Neuropsychologia*. 2002; 40:1196–1208. [PubMed: 11931923]
- Crawford JR, Garthwaite PH. Testing for suspected impairments and dissociations in single-case studies in neuropsychology: Evaluation of alternatives using Monte Carlo simulations and revised tests for dissociations. *Neuropsychology*. 2005; 19:318–331. [PubMed: 15910118]
- Cree GS, McRae K. Analyzing the factors underlying the structures and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns). *Journal of Experimental Psychology*. 2003; 132:163–201. [PubMed: 12825636]
- Crutch SJ, Warrington EK. The selective impairment of fruit and vegetable knowledge. *Cognitive Neuropsychology*. 2003; 20:355–372. [PubMed: 20957575]
- Dalrymple-Alford EC. Associative facilitation and interference in the Stroop color- word task. *Attention, Perception, and Psychophysics*. 1972; 11:274–276.
- Damasio H, Tranel D, Grabowski T, Adolphs R, Damasio A. Neural systems behind word and concept retrieval. *Cognition*. 2004; 92:179–229. [PubMed: 15037130]
- Farah MJ, McClelland JL. A computational model of semantic memory impairment: modality specificity and emergent category specificity. *Journal of Experimental Psychology: General*. 1991; 120:339–357. [PubMed: 1837294]
- Feeney DM, Baron JC. Diaschisis. *Stroke*. 1986; 17:817–830. [PubMed: 3532434]
- Forster K, Forster J. DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods*. 2003; 35:116–124.
- Friston KJ, Price CJ. Dynamic representations and generative models of brain function. *Brain Research Bulletin*. 2001; 54:275–285. [PubMed: 11287132]
- Gaffan D, Heywood CA. A spurious category-specific visual agnosia for living things in normal human and nonhuman primates. *Journal of Cognitive Neuroscience*. 1993; 5:118–128. [PubMed: 23972123]
- Gainotti G. The influence of gender and lesion location on naming disorder for animals, plants, and artefacts. *Neuropsychologia*. 2005; 43:1633–1644. [PubMed: 16009245]
- Gainotti G, Silveri MC. Cognitive and anatomical locus of lesion in a patient with a category-specific semantic impairment for living beings. *Cognitive Neuropsychology*. 1996; 13:357–389.
- Gallese V, Lakoff G. The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*. 2005; 22:455–479. [PubMed: 21038261]
- Garcea FE, Dombovy M, Mahon BZ. Preserved tool knowledge in the context of impaired action knowledge: Implications for models of semantic memory. *Frontiers in Human Neuroscience*. 2013; 7:1–18. [PubMed: 23355817]
- Gegenfurtner KR, Rieger J. Sensory and cognitive contributions of color to the perception of natural scenes. *Current Biology*. 2000; 10:805–808. [PubMed: 10898985]
- Glaser WR, Dungan FJ. The time course of picture word interference. *Journal of Experimental Psychology*. 1984; 10:640–654. [PubMed: 6238124]
- Glenberg AM, Kaschak MP. Grounding language in action. *Psychonomic Bulletin and Review*. 2002; 9:558–565. [PubMed: 12412897]
- Grill-Spector K, Kourtzi Z, Kanwisher N. The lateral occipital complex and its role in object recognition. *Vision Research*. 2001; 41:1409–1422. [PubMed: 11322983]
- Hart J, Berndt RS, Caramazza A. Category-specific naming deficit following cerebral infarction. *Nature*. 1985; 316:439–440. [PubMed: 4022134]
- Howard, D.; Patterson, K. *Pyramids and Palm Trees: A test of semantic access from pictures and words*. Bury St Edmunds, UK: Thames Valley Test Company; 1992.
- Hsu NS, Frankland SM, Thompson-Schill SL. Chromaticity of color perception and object color knowledge. *Neuropsychologia*. 2012; 50:327–333. [PubMed: 22192637]
- Hsu NS, Kraemer DJM, Oliver RT, Schlichting ML, Thompson-Schill SL. Color, context, and cognitive style: Variations in color knowledge retrieval as a function of task and subject variables. *Journal of Cognitive Neuroscience*. 2011; 23:2544–2557. [PubMed: 21265605]

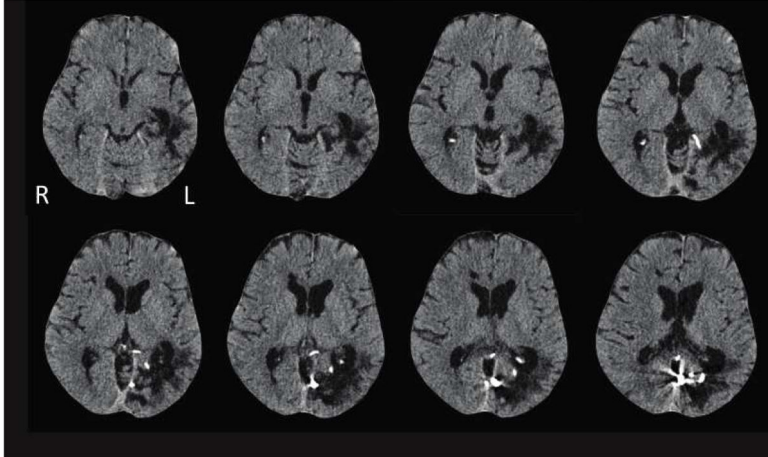
- Humphrey GK, Goodale MA, Jakobson LS, Servos P. The role of surface information in object recognition: studies of a visual form agnostic and normal subjects. *Perception*. 1994; 23:1457–1481. [PubMed: 7792135]
- Humphreys GW, Forde EME. Hierarchies, similarity, and interactivity in object recognition: “Category-specific” neuropsychological deficits. *Behavioral and Brain Sciences*. 2001; 24:453–509. [PubMed: 11682799]
- Jefferies E, Rogers TT, Lambon Ralph MA. Premorbid expertise produces category-specific impairment in a domain-general semantic disorder. *Neuropsychologia*. 2011; 49:3213–3223. [PubMed: 21816166]
- Johansson G. Visual perception of biological motion and a model for its analysis. *Perception and Psychophysics*. 1973; 14:201–211.
- Kourtzi Z, Kanwisher N. Activation in human MT/MST by static images with implied motion. *Journal of Cognitive Neuroscience*. 2000; 12:48–55. [PubMed: 10769305]
- Laiacona M, Barbarotto R, Capitani E. Semantic category dissociations in naming: is there a gender effect in Alzheimer’s disease? *Neuropsychologia*. 1998; 36:407–419. [PubMed: 9699949]
- Laiacona M, Capitani E. A case of prevailing deficit for non-living categories or a case of prevailing sparing of living categories? *Cognitive Neuropsychology*. 2001; 18:39–70. [PubMed: 20945206]
- Laws KR. Gender affects latencies for naming living and nonliving things. *Cortex*. 1999; 35:729–733. [PubMed: 10656639]
- Laws KR, Gale TM, Frank R, Davey N. Visual similarity is greater for line drawings of nonliving things than living things: the importance of musical instruments and body parts. *Brain and Cognition*. 2002; 48:421–424. [PubMed: 12030481]
- Lupker SJ. The semantic nature of response competition in the picture–word interference task. *Memory & Cognition*. 1979; 7:485–495.
- Luzzatti C, Davidoff J. Impaired retrieval of object-colour knowledge with preserved colour naming. *Neuropsychologia*. 1994; 32:933–950. [PubMed: 7969868]
- MacLeod CM. Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*. 1991; 109:163–203. [PubMed: 2034749]
- Mahon, BZ. Missed Connections: A connectivity constrained account of the representation and organization of object concepts. To appear. In: Margolis, E.; Laurence, S., editors. *Concepts: New Directions*. (in press)
- Mahon BZ, Caramazza A. Concepts and categories: A cognitive neuropsychological perspective. *Annual Review of Psychology*. 2009; 60:27–51.
- Mahon BZ, Caramazza A. What drives the organization of object knowledge in the brain? *Trends in Cognitive Sciences*. 2011; 15:97–103. [PubMed: 21317022]
- Mahon BZ, Costa A, Peterson R, Vargas K, Caramazza A. Lexical selection is not by competition: A reinterpretation of semantic interference & facilitation effects in the picture-word interference paradigm. *Journal of Experimental Psychology: Learning, Memory, & Cognition*. 2007; 33:503–535.
- Mahon BZ, Garcea FE, Navarrete E. Picture-word interference and the response exclusion hypothesis: A response to Mulatti and Coltheart. *Cortex*. 2012; 48:373–377. [PubMed: 22130091]
- Martin A, Haxby JV, Lalonde FM, Wiggs CL, Ungerleider LG. Discrete cortical regions associated with knowledge of color and knowledge of action. *Science*. 1995; 270:102–105. [PubMed: 7569934]
- Martin, A.; Ungerleider, LG.; Haxby, JV. Category-specificity and the brain: The sensory – motor model of semantic representations of objects. In: Gazzaniga, MS., editor. *The New Cognitive Neurosciences*. 2. Cambridge: MIT Press; 2000. p. 1023-1036.
- McKenna P, Parry R. Category specificity in the naming of natural and man-made objects: Normative data from adults and children. *Neuropsychological Rehabilitation*. 1994; 4:255–281.
- Meteyard L, Rodriguez-Cuadrado S, Bahrami B, Vigliocco G. Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*. 2012; 48:788–804. [PubMed: 21163473]
- Miceli G, Fouch E, Capasso R, Shelton JR, Tomaiuolo F, Caramazza A. The dissociation of color from form and function knowledge. *Nature Neuroscience*. 2001; 4:662–667.

- Powell J, Davidoff J. Selective impairments of object knowledge in a case of acquired cortical blindness. *Memory*. 1995; 3:435–461. [PubMed: 8574873]
- Price CJ, Warburton EA, Moore CJ, Frackowiak RSJ, Friston KJ. Dynamic diaschisis: Anatomically remote and context-sensitive human brain lesions. *Journal of Cognitive Neuroscience*. 2001; 13:419–429. [PubMed: 11388916]
- Roelofs A. Testing a non-decompositional theory of lemma retrieval in speaking – retrieval of verbs. *Cognition*. 1993; 47:59–87. [PubMed: 8482071]
- Rogers TT, Patterson K, Graham K. Colour knowledge in semantic dementia: it is not all black and white. *Neuropsychologia*. 2007; 45:3285–3298. [PubMed: 17804024]
- Rosinski RR. Picture–word interference is semantically based. *Child Development*. 1977; 48:643–647.
- Samson D, Pillon A. A case of impaired knowledge for fruit and vegetables. *Cognitive Neuropsychology*. 2003; 20:373–400. [PubMed: 20957576]
- Samson D, Pillon A, De Wilde V. Impaired knowledge of visual and non-visual attributes in a patient with a semantic impairment for living entities: A case of a true category-specific deficit. *Neurocase*. 1998; 4:273–290.
- Schriefers H, Meyer AS, Levelt WJM. Exploring the time course of lexical access in language production – picture-word interference studies. *Journal of Memory and Language*. 1990; 29:86–102.
- Shuren JE, Brott TG, Schefft BK, Houston W. Preserved color imagery in an achromatopsic. *Neuropsychologia*. 1996; 34:485–489. [PubMed: 8736561]
- Simmons KW, Ramjee V, Beauchamp MS, McRae K, Martin A, Barsalou LW. A common neural substrate for perceiving and knowing about color. *Neuropsychologia*. 2007; 4:2802–2810. [PubMed: 17575989]
- Snodgrass JG, Vanderwart M. A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*. 1980; 6:174–215. [PubMed: 7373248]
- Spalek K, Damian MF, Bölte J. Is lexical selection in spoken word production competitive? Introduction to the Special Issue on lexical competition in language production. *Language and Cognitive Processes*. 2013; 28:597–614.
- Stroop JR. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*. 1935; 18:643–662.
- Tanaka J, Weiskopf D, Williams P. The role of color in high-level vision. *Trends in Cognitive Sciences*. 2001; 5:211–215. [PubMed: 11323266]
- Thompson-Schill SL, Aguirre GK, Desposito M, Farah MJ. A neural basis for category and modality specificity of semantic knowledge. *Neuropsychologia*. 1999; 37:671–676. [PubMed: 10390028]
- Thompson-Schill SL. Neuroimaging studies of semantic memory: inferring “how” from “where”. *Neuropsychologia*. 2003; 41:280–292. [PubMed: 12457754]
- Vigliocco G, Vinson DP, Indefrey P, Levelt WJM, Hellwig F. Role of grammatical gender and semantics in German word production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2004; 30:483–497.
- Vinson DP, Vigliocco G, Cappa S, Siri S. The breakdown of semantic knowledge along semantic field boundaries: Insights from an empirically-driven statistical model of meaning representation. *Brain & Language*. 2003; 86:347–365. [PubMed: 12972366]
- Warrington EK, McCarthy R. Category specific access dysphasia. *Brain*. 1983; 106:859–878. [PubMed: 6652466]
- Warrington EK, McCarthy RA. Categories of knowledge: further fractionations and an attempted integration. *Brain*. 1987; 110:1273–1296. [PubMed: 3676701]
- Warrington EK, Shallice T. Category specific semantic impairments. *Brain*. 1984; 107:829–853. [PubMed: 6206910]
- Zwaan, RA. The immersed experience: Toward an embodied theory of language comprehension. In: Ross, BH., editor. *The psychology of language and motivation*. Vol. 44. New York: Academic Press; 2004.

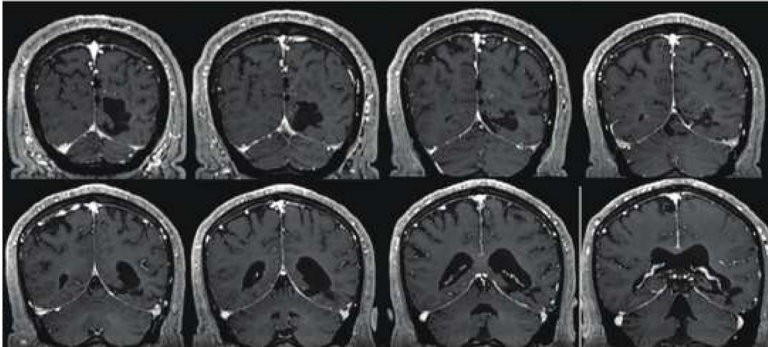
Panel A.



Panel B.



Panel C.



Panel D.



Figure 1. AC's lesion and object-color knowledge impairment

Panels A–C illustrate AC's left hemispheric lesion. Panel A (T1-weighted MRI images obtained ten days post-hemorrhage) depicts both intraventricular and intraparenchymal hemorrhage in the sagittal plane, illustrating extensive intraparenchymal hemorrhage within both the occipital and temporal lobes. In Panel B, sequential axial CT images (shown superior to inferior) obtained two months post-hemorrhage, with infarcted tissue appearing hypodense relative to surrounding parenchyma. The linear serpiginous hyperdensities within infarcted tissue are vessel casts made by the embolic material used to cure the dural

arteriovenous fistula. Panel C (T1 MRI images obtained 1.5 years post-hemorrhage) depicts the lesion in the coronal plane. Panel D contains examples of some of the black and white drawings that AC was instructed to color with a marker, and illustrates the impairment to object-color knowledge.

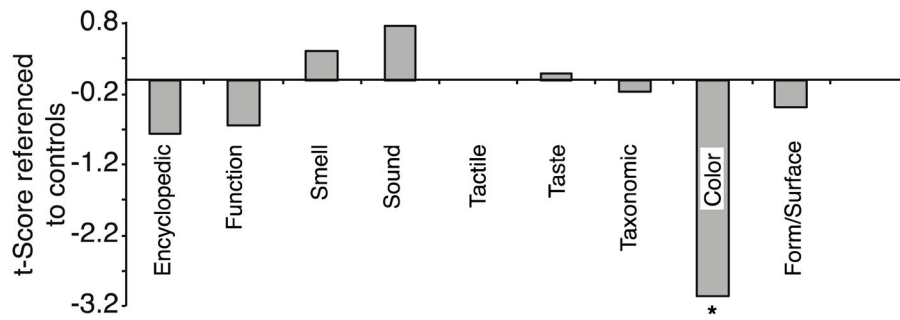


Figure 2. Case AC's performance on the Semantic Attribute Questionnaire

This figure plots t-scores comparing AC's performance to controls for different knowledge types in the Semantic Attribute Questionnaire. A significant impairment relative to controls is indicated by an asterisk ($p < 0.05$).

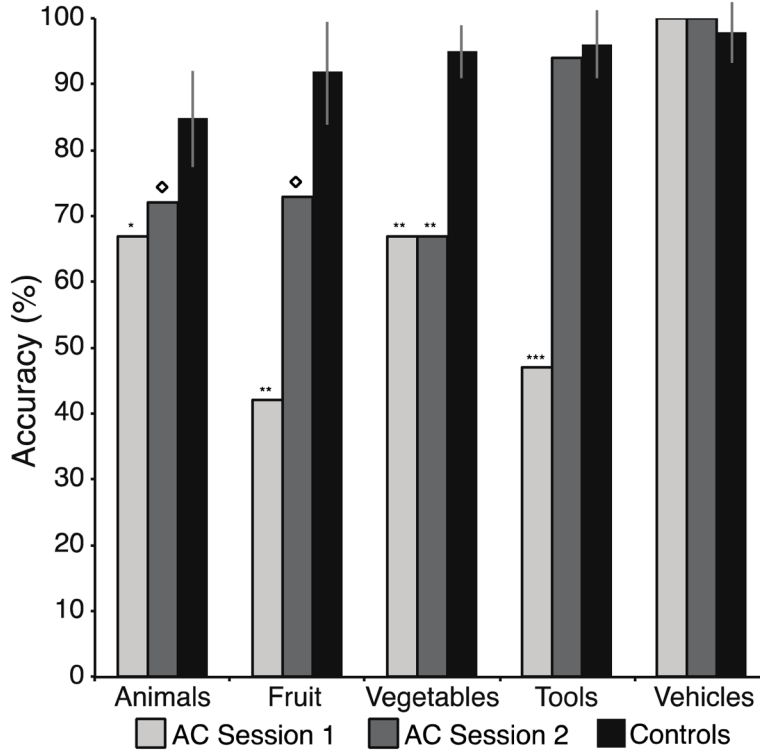


Figure 3. Case AC and controls' accuracy for Naming the Typical Colors of Objects
This figure plots accuracy on an object-color knowledge task in which AC and controls named the prototypical color of Snodgrass and Vanderwart objects. Asterisks indicate a significant difference between the patient and controls' performance (t-test; Crawford and Garthwaite, 2002; * = $p < 0.05$; ** = $p < 0.01$, and *** = $p < 0.001$). Diamonds indicate a marginal impairment ($p = 0.05$, $p = 0.06$). Error bars represent the standard error of the mean for controls.

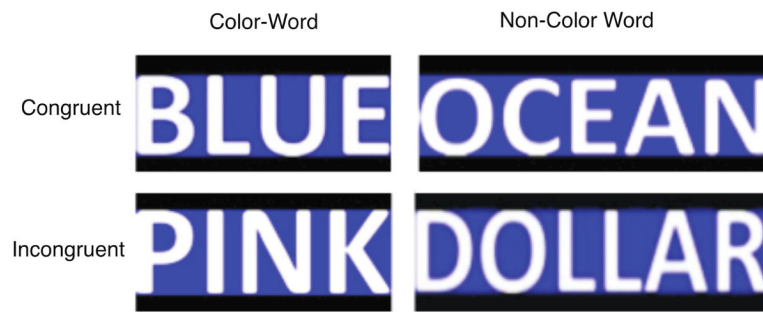


Figure 4.
Example of conditions and stimuli used in the Stroop Task.

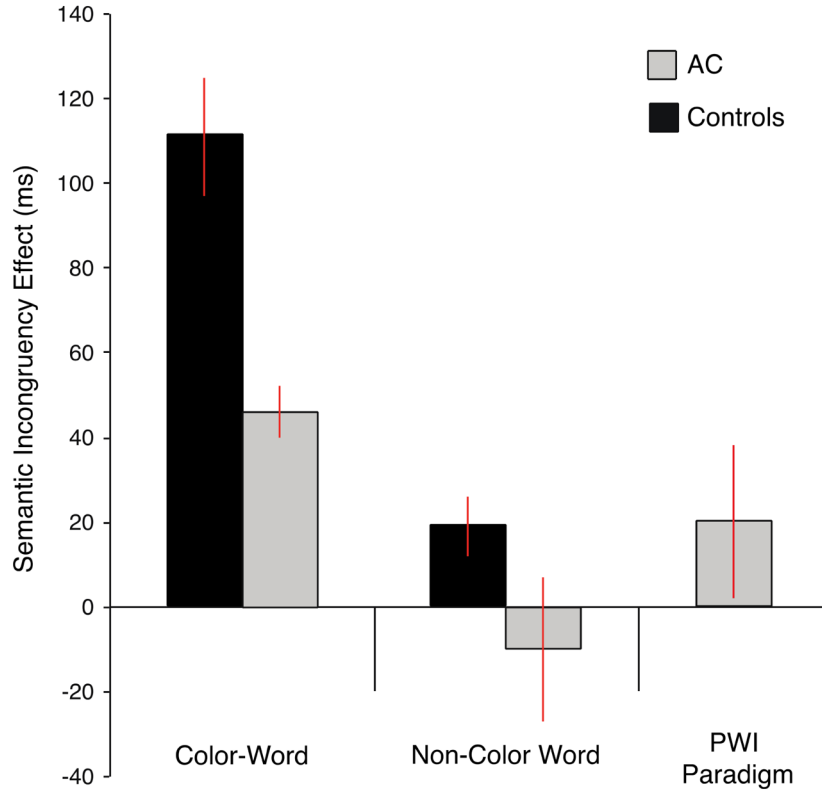


Figure 5. Semantic incongruity effects for AC and controls on the Stroop and Picture-Word Interference Tasks

This figure plots the magnitude of the semantic incongruity effects for AC and controls (calculated by subtracting congruent latencies from incongruent latencies) for the color-word and non-color word conditions of the Stroop Task and for the Picture-Word Interference task. Error bars represent standard error of the mean latencies for controls (control data are from Mahon et al., 2012).

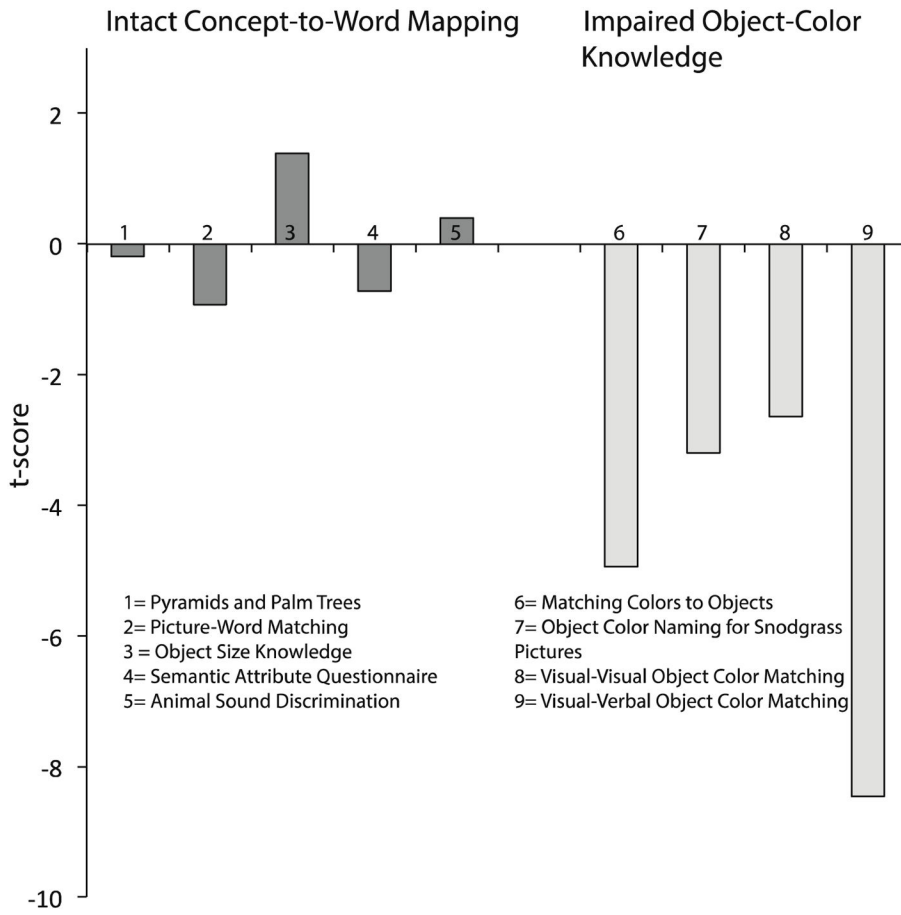


Figure 6. Intact general concept-to word mapping and impaired object-color knowledge for visual tasks

The left side of the figure plots performance on tasks that require mapping of words onto concepts (Tasks 1–5; note ‘Animal Sound Discrimination’ is from Supplemental Materials). AC’s performance on these tasks is not significantly different from controls. The right side of the figure plots performance on object-color knowledge tasks (Tasks 6–9). AC’s performance on these tasks is significantly different from controls. These data indicate that AC’s object-color knowledge impairment cannot be explained by a general inability to map a word onto its concept. A t-score of –2 and lower indicates an impairment relative to controls.

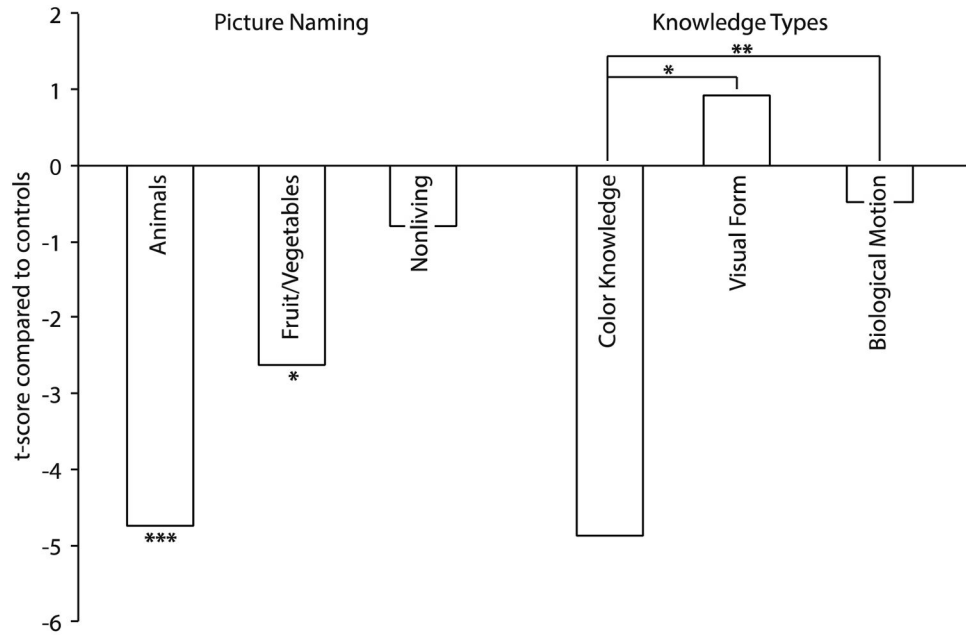


Figure 7. Summary of Case AC’s principal dissociations

This figure depicts t-scores comparing AC’s accuracy to controls’ for Snodgrass picture naming, separated by category, as well as aggregate performance across multiple tasks accessing the integrity of visual form, visual color and biological motion knowledge. Performance was also collapsed across multiple testing sessions. Asterisks on the left panel indicate impairment relative to controls (t-test; Crawford and Garthwaite, 2002) and asterisks on the right represent a significant difference between tasks, referenced to controls (RSDT; Crawford and Garthwaite, 2005). ** = $p < 0.01$; * = $p < 0.05$.

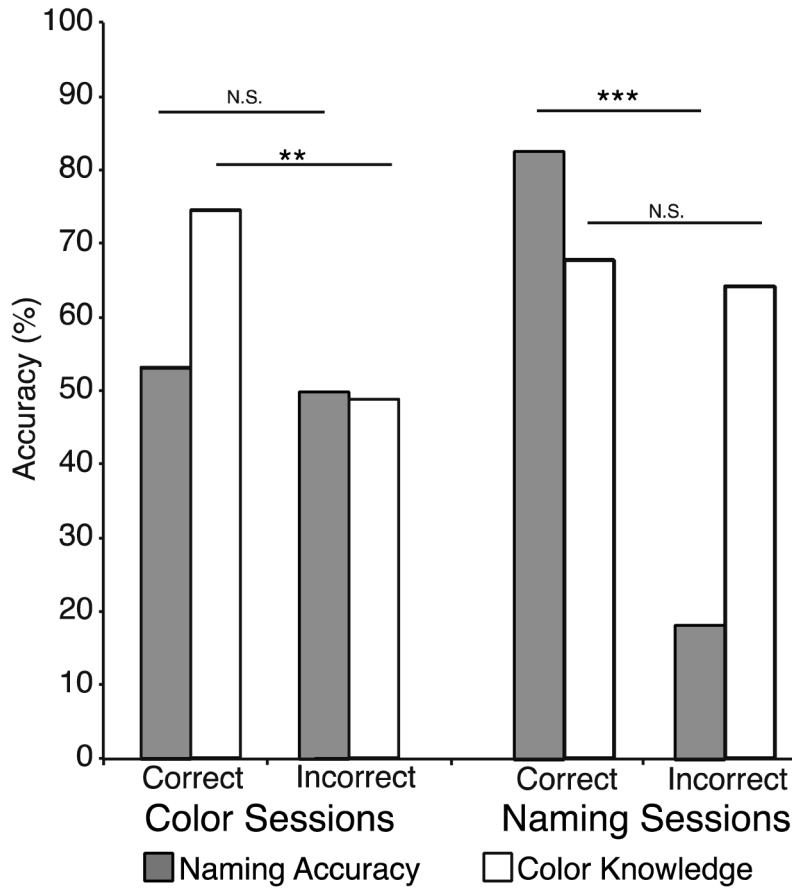


Figure 8. Color knowledge and picture naming performance for the same items are unrelated
This figure shows an item-based analysis of naming performance contingent on color knowledge, and color knowledge contingent on naming performance. On the left side, data are binned according to whether AC was correct/incorrect for color knowledge, and on the right side, data are binned according to correct/incorrect naming performance (see text for details). ** = $p < 0.01$; *** = $p < 0.001$.

Panel A. Modality and Domain are Orthogonal Panel B. Modality and Domain-Specific Connections Constraints

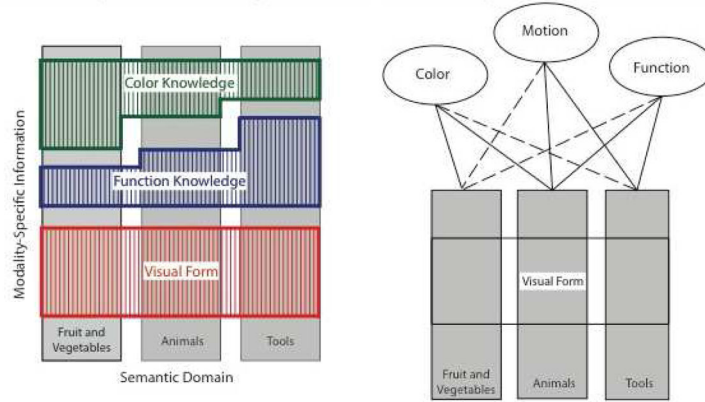


Figure 9. Schematic Illustrations of Two Possible Ways in which Domain and Modality could Jointly Constrain the Organization of Object Knowledge

Schematics showing two possible organizational frameworks for how modality and domain could jointly constrain the organization of conceptual knowledge. Panel 9a illustrates a possible architecture of conceptual organization in which domain and modality are truly orthogonal dimensions of organization. Panel 9b shows another possible organization in which modalities are not distributed within domains, but selective impairment to object-color knowledge could arise due to a selective disconnection deficit.

Table 1a

Mid to High Level Visual Processing

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and the testing dates for various tests of Mid to High Level Visual Processing.

	Control sample		AC's score		Significance test		Test date
	N	%	SD	%	t	p	
HUMAN MOTION	6	0.99	0.02	1	0.46	0.66	07/11
ANIMAL MOTION	3	0.96	0.02	0.94	-0.87	0.48	06/13
COLOR NAMING (1)	6	0.85	0.1	0.78	-0.65	0.54	08/11
COLOR NAMING (2)	6	0.85	0.1	1	1.39	0.22	09/11
COLOR NAMING (3)	-	-	-	1	-	-	06/13
COLOR-NAME MATCHING	-	-	-	1	-	-	10/11
COLOR NAME CATEGORIZATION	-	-	-	1	-	-	06/13
ISHIHARA PLATES (short)	-	-	-	1	-	-	09/11
ISHIHARA PLATES (long)	-	-	-	0.97	-	-	06/13
PART-MATCHING TEST	6	0.94	0.07	0.94	0	1.0	08/11

Birmingham Object Recognition Battery

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and the testing dates for various tests of the integrity of mid and high level visual processing as assessed by the Birmingham Object Recognition Battery (BORB).

Table 1b

	Control sample			AC's score		Significance test		Test Date
	N	%	SD	%	t	p		
B.O.R.B								
Length Match Task	39	0.9	0.05	0.89	-0.2	0.84	0.84	09/11
Size Match Task	39	0.91	0.08	0.88	-0.37	0.71	0.71	09/11
Orientation Match Task	39	0.83	0.09	0.87	0.44	0.66	0.66	09/11
Position of Gap Match Task	39	0.88	0.11	0.84	-0.36	0.72	0.72	09/11
Minimal Feature View Task	30	0.93	0.08	0.84	-1.11	0.28	0.28	09/11
Foreshortened View Task	30	0.86	0.1	0.96	0.98	0.33	0.33	09/11
Object Reality A - hard	14	0.84	0.07	0.84	0	1	1	09/11
Object Reality A - easy	14	0.9	0.08	0.94	0.48	0.64	0.64	09/11
Object Reality B - hard	32	0.79	0.15	0.84	0.33	0.74	0.74	09/11
Object Reality B - easy	13	0.95	0.04	0.91	-0.96	0.35	0.35	09/11
Item Match Task	34	0.94	0.05	1	1.18	0.25	0.25	09/11
Associative Match Task	15	0.92	0.08	0.88	-0.73	0.48	0.48	09/11
Picture Naming (short version)	34	0.85	0.15	0.4	-2.96	0.006	0.006	09/11
Picture Naming (long version)	11	0.93	0.04	0.82	-2.63	0.025	0.025	09/11

Table 2

Object Decision

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and the testing dates for the Object Decision task.

OBJECT DECISION	Control sample		AC's score		Significance test		Test date
	N	%	SD	%	t	p	
10 sec	6	0.89	0.02	0.91	0.93	0.40	07/11
1 sec	-	-	-	0.89	-	-	08/11
500 ms	-	-	-	0.9	-	-	09/11
200 ms	-	-	-	0.81	-	-	09/11

Table 3

Snodgrass Picture Naming

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), and t- and p- scores for 3 different sessions of the Snodgrass and Vanderwart black and white picture naming. Control name agreement values are derived from Snodgrass and Vanderwart (1980). Session 1 took place in July of 2011, Session 2 in August of 2011 and Session 3 in September of 2011.

	Control sample		AC's score			Significance test						
	N	%	SD	Session 1	Session 2	Session 3	t	p				
PICTURE NAMING												
Animals	42	0.89	0.09	0.18	0.55	0.55	-7.8	-3.73	<0.001	<0.001	<0.001	
Fruit	42	0.93	0.08	0.5	0.6	0.6	-5.31	-4.08	<0.001	<0.001	<0.001	
Vegetables	42	0.78	0.15	0.4	0.5	0.7	-2.5	-1.85	-0.53	0.02	0.07	0.6
Body Parts	42	0.9	0.08	0.89	0.89	1	-0.12	-0.12	1.24	0.9	0.9	0.22
Music	42	0.87	0.13	0.5	0.4	0.4	-2.81	-3.57	-3.57	0.008	0.001	0.001
Furniture	42	0.87	0.2	0.7	0.8	0.7	-0.84	-0.35	-0.84	0.41	0.73	0.41
Tools	42	0.87	0.2	0.6	0.5	0.7	-1.33	-1.83	-0.84	0.19	0.07	0.41
Vehicles	42	0.87	0.12	0.7	0.9	1	-1.4	0.25	1.07	0.17	0.81	0.29

Table 4

Conceptual Knowledge of Objects

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and the testing dates for various tasks accessing AC's conceptual knowledge of objects.

	Control sample		AC's score		Significance test		Test date
	N	%	SD	%	t	P	
NAMING FROM DEFINITION							
Animals	6	0.91	0.05	0.67	-4.44	0.007	08/11
Fruit	6	0.8	0.11	0.33	-3.96	0.01	08/11
Vegetables	6	0.83	0.08	0.6	-2.66	0.04	08/11
Body Parts	6	0.98	0.04	0.9	-1.85	0.12	08/11
Musical Instruments	6	0.85	0.06	0.56	-4.48	0.007	08/11
Furniture	6	0.93	0.12	0.9	-0.23	0.83	08/11
Tools	6	0.92	0.14	0.67	-1.65	0.16	08/11
Vehicles	6	0.83	0.06	0.67	-2.47	0.06	08/11
PYRAMIDS AND PALM TREES	6	0.89	0.05	0.88	-0.19	0.86	08/11
PICTURE-WORD MATCHING	6	0.98	0.01	0.97	-0.93	0.4	08/11
KNOWLEDGE OF OBJECT SIZE	6	0.93	0.02	0.96	1.39	0.22	09/11
COLOR OF NATURAL AND MAN-MADE ITEMS							
Natural Items	6	0.88	0.08	0.6	-3.24	0.02	08/11
Man-made Items	6	0.94	0.03	0.77	-5.25	0.003	08/11
MATCHING COLORS TO OBJECTS (1)	6	0.94	0.03	0.73	-6.48	0.001	08/11
MATCHING COLORS TO OBJECTS (2)	6	0.94	0.03	0.83	-3.4	0.019	10/11

Table 5

Semantic Attribute Questionnaire by Category

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and testing date for the Semantic Attribute Questionnaire.

	Control sample		AC's score	Significance test		Test date
CATEGORY	N	%	SD	%	t	p
Animals	12	0.96	0.06	0.93	-0.48	0.64 08/11
Fruit	12	0.95	0.04	0.91	-0.96	0.36 08/11
Tools	12	0.98	0.04	0.94	-0.96	0.36 08/11
Vehicles	12	0.97	0.04	0.95	-0.48	0.64 08/11

Table 6

Naming Living vs. Non-Living Items: RSDT Analyses for Snodgrass Picture Naming and Naming from Definition Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), correlation between tasks, and t- and p- scores for a RSDT analysis comparing performance for living versus non-living items, referenced to controls for both Snodgrass Picture Naming and Naming from Definition. Note: for this particular Snodgrass Picture Naming analysis, control values came from 19 healthy undergraduates who named the 60 items. The categories of animals, fruit, and vegetables (living) and tools, vehicles, and furniture (non-living) are included in these analyses.

	Control Sample		AC's score		Correlation	Significance test	
	N	%	SD	%		t	P
PICTURE NAMING							
Living	19	0.9	0.06	0.50	0.43	3.9	0.001
Non-Living	19	0.88	0.07	0.73			
NAMING FROM DEFINITION							
Living	6	0.85	0.08	0.53	0.64	2.37	0.06
Non-Living	6	0.89	0.11	0.75			

Table 7

Object-color Naming for Snodgrass and Vanderwart Pictures

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score) and t- and p-scores for two sessions when AC provided the typical color of a given object from various categories. Session 1 took place in August of 2011 and Session 2 took place in November of the same year.

CATEGORY	Control sample		AC's score		Significance test				
	N	%	SD	%	Session 1	Session 2	t	p	
Animals	6	0.85	0.05	0.67	0.72	-3.33	-2.41	0.02	0.06
Fruit	6	0.92	0.07	0.42	0.73	-6.61	-2.51	0.001	0.05
Vegetables	6	0.95	0.06	0.67	0.67	-4.32	-4.32	0.008	0.008
Tools	6	0.96	0.05	0.47	0.94	-9.07	-0.37	<0.001	0.73
Vehicles	6	0.98	0.04	1	1	0.46	0.46	0.66	0.66

Table 8

Categorizing and Defining Objects

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score) and t- and p-scores for when AC and controls provided information about various knowledge types for the categories of animals, fruit, vegetables, tools, and vehicles.

	Control sample		AC's score		Significance test	
	N	%	SD	%	t	p
ANIMALS						
Number of legs	3	0.94	0.04	0.87	-1.52	0.27
Color	3	0.90	0.07	0.60	-3.71	0.067
Climate	3	0.95	0.06	0.97	0.29	0.8
Dangerous/Friendly	3	0.94	0.03	1	1.73	0.23
Size	3	0.97	0.05	0.91	-1.04	0.41
Food	3	0.90	0.06	0.97	1.01	0.42
Motion	3	0.98	0.02	0.95	-1.3	0.32
FRUIT						
Where they grow	3	0.94	0.07	1	0.74	0.54
Color	3	0.98	0.04	0.71	-5.85	0.03
Taste	3	0.95	0.08	1	0.54	0.64
Function	3	0.94	0.14	0.98	0.25	0.83
Texture	3	0.99	0.01	0.93	-5.2	0.04
Size	3	0.99	0.01	0.89	-8.67	0.01
Shape	3	0.94	0.14	0.96	0.12	0.91
Seeds/Pits	3	0.93	0.09	0.89	-0.39	0.74
VEGETABLES						
Where they grow	3	0.97	0.06	0.92	-0.72	0.55
Color	3	0.96	0.04	0.74	-4.76	0.04
Taste	3	0.85	0.24	1	0.54	0.64
Function	3	0.92	0.17	0.94	0.1	0.93
Texture	3	0.99	0.01	1	0.87	0.48
Size	3	0.94	0.1	0.83	-0.95	0.44

	Control sample		A.C.'s score		Significance test	
	N	%	SD	%	t	p
Shape	3	0.98	0.04	0.94	-0.87	0.48
Seeds/Pits	3	0.99	1	1	0.87	0.48
TOOLS						
Function	3	0.99	0.02	0.98	-0.43	0.71
Shape	3	0.99	0.01	0.96	-2.6	0.12
Size	3	0.98	0.03	0.87	-3.18	0.09
Color	3	0.9	0.06	0.96	0.87	0.48
VEHICLES						
Function	3	1	0.001	1	0	1
Size	3	0.98	0.04	1	0.43	0.71
Shape	3	0.97	0.07	1	0.37	0.75
Mode of transport	3	1	0.001	1	0	1
Color	3	0.89	0.09	0.46	-4.14	0.05

Table 9

Modality-Specificity of the Object-Color Knowledge Impairment

Control participants (N), mean control proportion correct (%), control standard deviation (SD), AC's proportion correct (AC's score), t- and p-scores, and the testing dates for when AC made decisions on three tasks of object-color knowledge that tested all modalities of input.

Control sample		AC's score	Significance test		Test date
N	%	SD	%	t	p
GENERATION OF TYPICAL COLORS OF OBJECTS					
6	0.9	0.05	0.69	-3.89	0.01 10/11
6	0.97	0.04	0.75	-5.09	0.004 10/11
6	0.94	0.07	0.67	-3.57	0.016 10/11
VISUAL-VISUAL OBJECT COLOR MATCHING					
6	0.89	0.05	0.75	-2.59	0.049 10/11
6	0.97	0.04	0.92	-1.16	0.3 10/11
6	0.94	0.07	0.83	-1.46	0.21 10/11
6	0.89	0.05	0.63	-4.81	0.005 05/13
6	0.97	0.04	0.73	-5.56	0.003 05/13
6	0.94	0.07	0.92	-0.27	0.8 05/13
VISUAL-VERBAL OBJECT COLOR MATCHING					
52	0.87	0.04	0.71	-3.7	0.014 10/11
12	0.97	0.04	0.58	-9.03	<0.001 10/11
12	0.99	0.03	0.58	-12.65	<0.001 10/11