‘Yellow’ or ‘Gold’?: Neural Processing of Gloss Information

Hidehiko Komatsu[1,2], Akiko Nishio[1], Gouki Okazawa[1,2], and Naokazu Goda[1,2]

[1] Division of Sensory and Cognitive Information,
National Institute for Physiological Sciences, Okazaki 444-8585, Japan
[2] Department of Physiological Sciences,
Graduate University for Advanced Studies (SOKENDAI), Okazaki 444-8585, Japan
komatsu@nips.ac.jp

Abstract. Although color term ‘Gold’ is commonly used, traditional color science cannot deal with ‘Gold’ because there is no region corresponding to ‘Gold’ in the chromaticity diagram generated based on the color matching experiments. Appearance of an object changes from ‘Yellow’ to ‘Gold’ with an increase in the specular reflectance, and understanding how we discriminate ‘Gold’ from ‘Yellow’ is tightly related to an important problem of how we perceive surface reflectance or gloss of objects. To understand neural processes underlying gloss perception, we conducted a series of experiments. When we compared neural activities evoked by objects with specular and matte surfaces using functional magnetic resonance imaging in monkeys, stronger activities to specular surface were observed in areas along the ventral pathway of the visual cortex including the inferior temporal (IT) cortex that plays an essential role in object discrimination. We also recorded single neuron activities from the IT cortex and found that there exist neurons that are selectively responding to specific gloss, and that as a population, these neurons systematically represented a variety of glosses. We speculate that visual features distinguishing surface glosses are detected in early visual areas and this information is integrated along the ventral visual pathway to form neural representation of a variety of glosses of object images in the IT cortex. Neural mechanisms underlying discrimination between ‘Gold’ and ‘Yellow’ should at least in part lie in this process.

Keywords: Gold, Color naming, Gloss, Neuron, Monkey.

1 Is ‘Gold’ a Color?

Suppose you are viewing the image of Golden mask of Tutankhamun on a display monitor. If you view it from a distance, it appears to be golden. However, if you carefully look at it in a short distance, you will notice that the image consists of only regions with ordinary colors such as yellow, brown or black. Although there exist regions corresponding to these colors in the chromaticity diagram, there is no region corresponding to gold [1–3]. What does this mean? One answer may lie in the fact that color term gold is closely related to the material and surface

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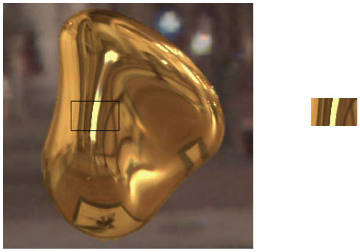

Fig. 1. (Left) Computer graphics (CG) image of a golden object. (Right) A cut out from the golden object indicated by a rectangle. The whole object appears golden, but the cut out no longer appears golden. Courtesy of Isamu Motoyoshi.

coating of real objects. Three-dimensional structures of real objects yield complex shading pattern and distortions of reflected images of surrounding scenes, and perception of gold may be related to such complicated structure of the luminance/color patterns on the object surface. This suggests that when regions with various colors and luminances are orderly arranged within an object image under some rule that is consistent with shadings and reflected images on the surface of gold objects, this object comes to possess appearance of gold. Figure 1 shows such an example. On the left is a computer graphics (CG) image of a gold object that appears golden. The right panel shows a cut out from the left image and this no longer has gold appearance; rather, it appears as an image in which yellow, brown or black regions are arranged. Thus some global processing to extract information on the spatial structure of the luminance and color pattern should underlie the gold perception. On the other hand, previous physiological studies on color representation have dealt with colors that are defined on the chromaticity diagram [4–6]. The subjects of these studies were to describe the properties of local colors that can be seen through a small aperture and to analyze the processing of such information. Some studies have explored the effects of surrounding context to understand the neural mechanisms of color constancy or color induction [7–9], but global contexts dealt with in these studies seem quite different from those related to yielding perception of gold. In short, previous physiological studies on color vision have mainly dealt with the processing of the cone signals in the local visual field, i.e. questions on local processing, with or without surrounding context. However, to understand the mechanisms of gold perception, we will have to deal with some global processing related to the extraction of spatial structure of luminance and color signals.

2 Neural Processing of Color Information

With regard to the processing of local color information, a large amount of knowledge has been already accumulated. Figure 2 shows the neural pathway related

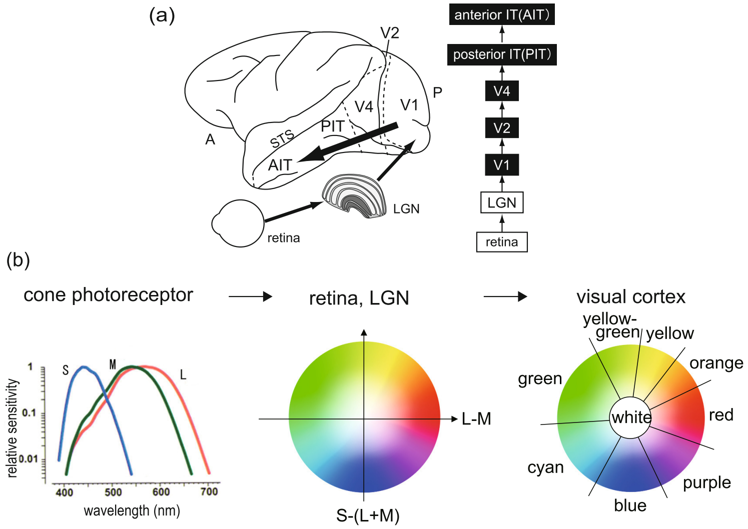

Fig. 2. (a) Neural pathway related to color vision in monkey visual system. To the right, open box indicates subcortical stage, solid box indicates cortical stage. LGN: lateral geniculate nucleus, V1: primary visual cortex, V2: area V2, V4: area V4, IT: inferior temporal cortex, STS: superior temporal sulcus, A: anterior, P: posterior. (b) Schematic illustration of how color information is represented at different stages along the visual pathway depicted in (a).

to color vison, and schematically illustrates how color information is represented at different stages along this pathway. Visual information is decomposed into the signals of three types of cones, and color signals are extracted by subtraction of signals between different types of cones. These processes are done within the retinal circuit to generate two types of cone-difference signals, namely 'L - M' (or 'M - L') and 'S - (L+M)' signals (two-axes color representation). These cone-difference signals are transmitted through the lateral geniculate nucleus to the primary visual cortex (V1). In V1, these two types of cone-difference signals are combined to form neurons selectively responsive for particular ranges of hues or saturation (multi-axes color representation) [8, 10, 11]. Multi-axes color representation is the ubiquitously observed way of color representation in cortical visual areas related to color processing including extrastriate areas V2, V4 and the inferior temporal (IT) cortex [12–16]. At the highest stage of this pathway, it has been shown that activities of IT neurons that are selective for particular hues are closely related to the behaviors based on color perception [17, 18]. Then how can we think about the neural machinery related to gold perception that requires global processing? The hints for this question must lie in the properties of gold as described above. That gold is closely related to object vision and that global processing is required suggests that higher visual areas related to object vision are involved in the perception of gold. Visual cortical areas consist of hierarchically organized multiple stages. At the earliest stage in V1, local visual information within a small receptive field is processed, and as the stage becomes higher gradually more global processing becomes possible by the expansion of the receptive fields that enables integration of spatial information. It is well established that the ventral visual pathway connecting V1 and the IT cortex is essential for object vision, and the neural machinery for gold perception may lie in the higher stage in this pathway.

3 Global Color and Perception of Gloss

In the real world, a particular visual perception occurs in relation to some physical events. Now, let's consider the gold perception from a viewpoint of physical properties of objects related to gold perception. In general, three physical factors are involved in the formation of an object image, namely three-dimensional structure of the object, surface reflection property and illumination environment. Of these three, surface reflection property is the one most closely related to gold perception. This is evident from the results of color naming experiment showing that images of objects with high specular reflectance and specific range of color yield gold perception [19]. In this experiment, we generated CG images of objects with various ratios between the specular reflectance (strength of specular reflection) and diffuse reflectance (strength of diffuse reflection),

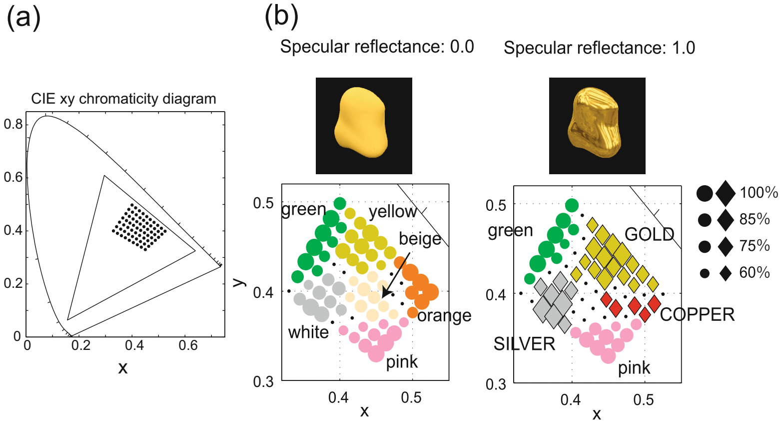

Fig. 3. Stimulus and results of color naming experiment using CG image of objects as stimuli. In this experiment, subjects selected the color of a stimulus from 15 color terms including 11 basic color terms (red, orange, yellow, green, blue, purple, pink, brown, white, gray, black), beige, Gold, Silver, Copper. (a) Dots indicate the 67 CIE xy chromaticity coordinates of the stimuli used in the experiment. All pixels in each stimulus had the same chromaticity coordinate. (b) Results from the categorical color-naming task for stimuli with specular reflectance of 0.0 (left) and 1.0 (right). Each symbol at the bottom indicates the color term named in more than 50% of trials for the stimulus with the corresponding chromaticity. 'Gold' is used only for stimulus with high specular reflectance. From [19] with modification.

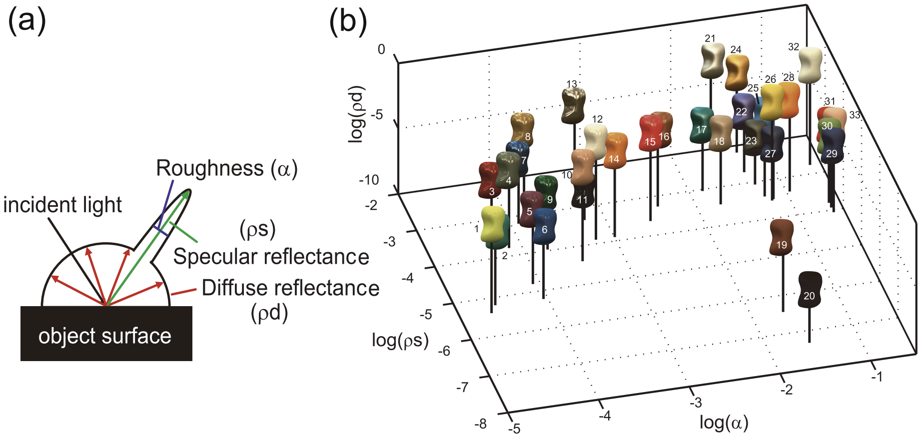

Fig. 4. (a) Schematic illustration of three reflection parameters, diffuse reflectance (ρd), specular reflectance (ρs) and roughness (α). ρd indicates the strength of the diffuse reflection, ρs indicates the strength of specular reflection, and α indicates the microscopic unevenness of the surface that causes the spread of specular reflection. As ρd increases, the object becomes lighter. As ρs increases, the highlight becomes stronger, whereas as α increases, the highlight becomes blurred. (b) Examples of a stimulus set used to test gloss selectivity of IT neurons and their distribution in the reflection parameter space. From [26] with modification.

and that have a constant chromaticity coordinate across the object image. We then asked subjects to name the color of each image. Color term 'Gold' was stably used for specific range of chromaticities around yellow with stimuli having large specular reflectance but not for stimuli having low specular reflectance (Figure 3). This indicates that, in order to understand the mechanisms of gold perception, we need to understand more general question about how the visual system distinguish objects with different surface reflectance properties. In other words, understanding the mechanisms of gloss perception should provide an important hint.

Although no physiological study has been done to examine neural mechanisms of gloss perception, many psychophysical studies have been conducted [20–24]. Importance of highlight on gloss perception has been recognized for a long time [25], and recent studies have uncovered the importance of spatial relationships between highlights and diffuse shadings or the object shape [22] although visual features related to gloss perception are not yet completely understood. With regard to the physical properties of surface reflection, three parameters, namely specular reflectance (ρs), diffuse reflectance (ρd) and surface roughness (α) are shown to be important (Figure 4a), and CG programs commonly manipulate these parameters to generate realistic images of objects with a variety of glosses. Therefore, in order to study neural representation of gloss, we prepared CG images of objects with various combinations of these parameters, and attempted to explore neurons that can discriminate gloss by recording and analyzing neural activities from the IT cortex that plays an essential role in object recognition.

4 Gloss Selective Neurons

We examined whether the neurons in the IT cortex of the monkeys are coding gloss of objects [26]. Visual stimuli consisted of images of custom made artificial three dimensional objects that have one of 33 surface reflectance properties and were rendered with natural illumination environment using Debevec's Light Probe Image Gallery (http://ict.debevec.org/~debevec/). We selected 33 types of surface reflectance properties that have distinct values of $\rho s, \rho d, \alpha$, and color from MERL BRDF database (http://www.merl.com/brdf/) that contains the surface reflectance data of about 100 real materials (Figure 4b). We tested responses of IT neurons to these stimuli while a monkey was performing a visual fixation task.

We found that there exist neurons in the lower bank of the superior temporal sulcus in the IT cortex that selectively responded to specific stimuli. Figure 5a shows the responses of an example of neurons that selectively responded to stimuli with a specific range of gloss. This neuron strongly responded to stimuli with sharp highlights (e.g. stimuli 8 and 13) and did not respond to either stimuli with blurred highlights or matte stimuli. Relationship between the response magnitudes and surface reflectance parameters is shown in Figure 5b. It can be clearly seen that this neuron selectively responded to stimuli with large ρs and small α. Although color widely changes across stimuli, this neuron showed responses to stimuli with sharp highlights regardless of the color, indicating that the color is not relevant for the selectivity.

This can be more clearly seen when we presented shuffled stimuli in which pixels of each stimulus in the original stimulus set were randomly re-arranged within the object contour. This manipulation maintains the average color or luminance of each stimulus but the glossiness dramatically changes, and Figure 6a shows that this neuron did not respond to the shuffled stimuli. On the other hand, the selectivity was largely maintained when the object shape or illumination condition was

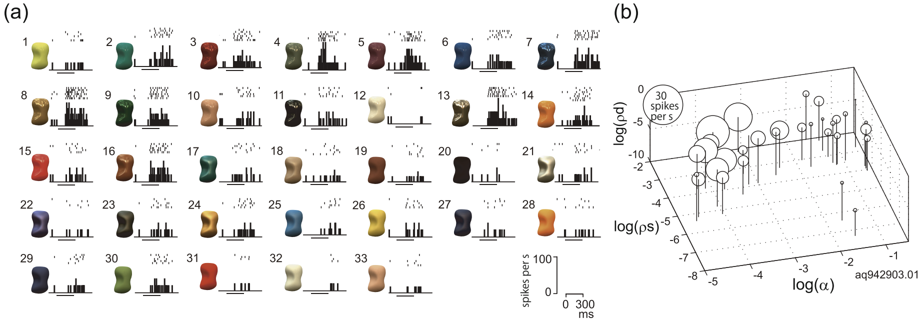

Fig. 5. Responses of an example of gloss selective IT neuron to the 33 stimuli with a variety of glosses. This neuron selectively responded to stimuli with sharp highlights. The responses are depicted as raster plots and post-stimulus time histograms (PSTHs) (a) and as the diameters of circles in the reflection parameter space (b). From [26] with modification.

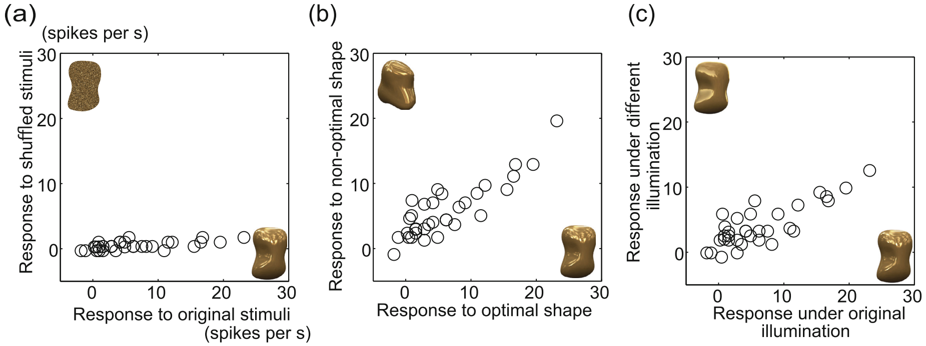

Fig. 6. (a) Relationship between responses to the original gloss stimulus set and those to the shuffled stimuli. No response was observed to the shuffled stimuli. (b) Relationship between the response to the gloss stimulus set with the optimal shape and those to the gloss stimulus set with an non-optimal shape. There was strong correlation between two sets of responses (r = 0.86). (c) Relationship between the responses to the gloss stimulus set rendered under the original illumination and those to the gloss stimulus set rendered under a different illumination. There was strong correlation between two sets of responses (r = 0.81). These results indicate that the selectivity was largely maintained when the object shape or illumination was changed. From [26] with modification.

changed (Figure 6b and c). These manipulations greatly change the spatial pattern of highlights as well as the pattern of shadings, but gloss perception is largely maintained. These results indicate that this IT neuron selectively responded to gloss, not to the irrelevant local image features or average luminance or color, and we regard this as an example of neurons that discriminate gloss (gloss selective neuron). Similarly, we recorded many gloss selective neurons from this area in the IT cortex that selectively responded to specific gloss and that maintained selectivity across the change in stimulus shape and illumination. Stimulus preference of these neurons differed from cell to cell: some preferred stimuli with sharp highlights (Figure 7a) like the neuron as depicted in Figure 5, some others preferred glossy stimuli with blurred highlights (with large ρs and large α)(Figure 7b), and some others even preferred matte stimuli (with large α and small ρs)(Figure 7c).

So far, 57 gloss selective neurons were recorded from two monkeys. Then, how is a variety of gloss encoded by the population of these neurons? If the neural population responded similarly to a pair of stimuli, we can think that these stimuli are regarded to have similar gloss by this population of neurons. In contrast, if the neural population responded differently to a pair of stimuli, these stimuli should be regarded to have different gloss. Knowing which pairs of stimuli were differentiated by the population of neurons and which pairs were not well differentiated will give a clue as to how different glosses are encoded by the gloss selective neurons. We computed the distance matrix for all pairs of 33 stimuli based on the responses of 57 gloss selective neurons in which distance was defined as 1 - correlation coefficient between the responses of a pair of

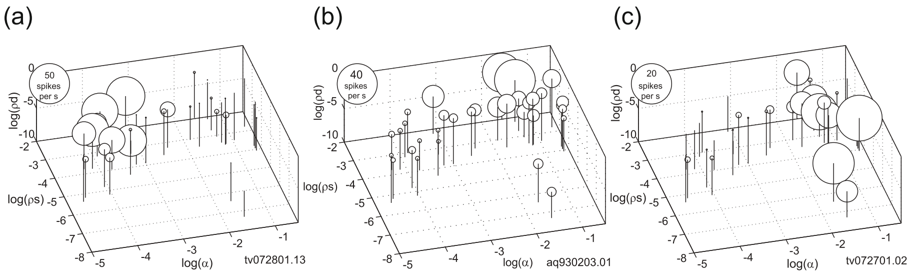

Fig. 7. Stimulus preference of three examples of gloss selective IT neurons. From [26] with modification.

stimuli, and applied Multi-Dimensional-Scaling (MDS) analysis to examine how the responses of this neuronal population represented gloss. Results of this MDS analysis is shown in a two dimensional plot in Figure 8 in which the distance relationships between each stimulus pair are preserved as much as possible. As can be seen, stimuli with similar glossiness are clustered in the diagram: highly specular stimuli are accumulated to the left, stimuli with blurred highlights are accumulated to the bottom right, and matte stimuli are accumulated at the top right. The results of the MDS analysis shows that population responses of these IT neurons encode a variety of gloss in a systematic way, and suggest that these IT neurons are coding visual information that is closely associated with characterizing surface gloss of objects.

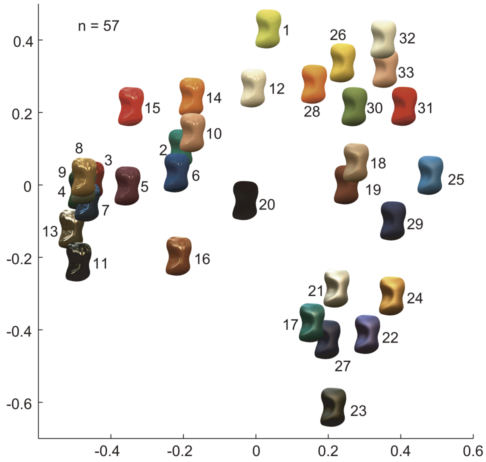

Fig. 8. Two-dimensional plot of the results of MDS analysis to examine how the population of gloss selective IT neurons represents a variety of gloss. From [26] with modification.

5 Cortical Areas Carrying Gloss Information

The results described above suggest that the IT cortex is involved in the discrimination of a variety of glosses. Local color information is shown to be processed along the ventral visual pathway and various colors are represented in the IT cortex [12, 14, 27]. Both gloss and color information are important surface attributes of objects, and they may be processed in similar pathways. To obtain whole view of the cortical regions activated by surface gloss, we conducted functional magnetic resonance imaging (fMRI) experiment in awake fixating monkeys [28]. While the monkey fixated on a central fixation spot on the screen in the MRI scanner, object images were presented. The images of glossy and matte objects were generated by using a CG software (Figure 9a). As a control condition for low-level image features, such as spatial frequency or luminance contrast, we generated scrambled images by locally randomizing the luminance phases of CG images using wavelet filters. When we contrasted the responses to images of glossy objects with the responses to images of both matte objects and the scrambled images, the activation was observed in areas along the ventral visual pathway including V1, V2, V3, V4 and the posterior part of the inferior temporal cortex (IT) in all hemispheres of two monkeys and middle part of IT at least in one monkey (Figure 9b). Judging from its location, this middle IT region likely corresponds to where we identified gloss selective neurons. The reason why this region is not strongly activated in the second monkey is likely due to the difference in the methodology between the neural recording experiment and fMRI experiment: In fMRI experiment, we searched for regions where glossy

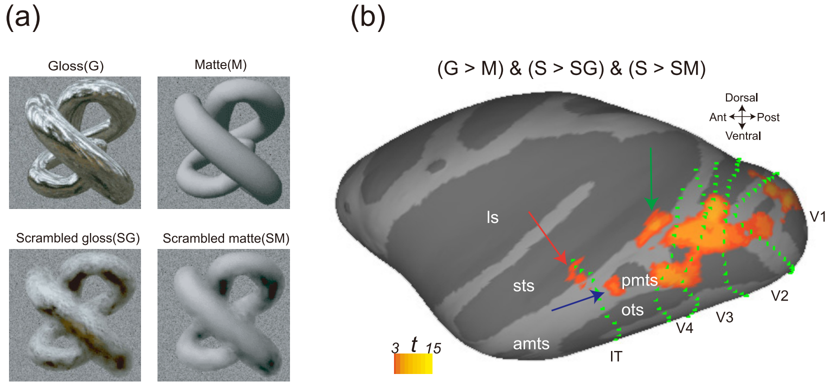

Fig. 9. (a) Glossy (G), matte (M), scrambled glossy (SG) and scrambled matte (SM) stimuli used to identify cortical regions activated by glossy objects. These stimuli were shown as movies in which the object rotated around the vertical axis. (b) The results of an fMRI experiment in a monkey showing the regions that were more responsive to glossy stimuli (G) than to other stimuli (M, SG, SM) identified by conjunction analysis. ls: lateral sulcus, sts: superior temporal sulcus, amts: anterior middle temporal sulcus, pmts: posterior middle temporal sulcus, ots: occipito-temporal sulcus. From [28] with modification.

stimuli yielded stronger activation, whereas in the neural recording experiment we searched for neurons that discriminate gloss regardless of whether it preferred glossy stimuli or matte stimuli. In another control experiment, we manipulated the contrasts of images and found that the activations observed by the glossy stimuli cannot be solely explained by the global or local contrasts. These results suggest that image features related to gloss perception are processed along the ventral visual pathway from V1 to specific regions in the IT cortex. This is consistent with previous observations in human fMRI experiments that showed surface properties of objects are processed in the ventral visual pathway.

The results of this fMRI experiment may seem to suggest that gloss and color information share the same visual pathway. However, when we compare the activations evoked by color stimuli and glossy stimuli in the IT cortex, they only partly overlapped each other. This suggests that although processing of gloss and color information share the ventral visual pathway, actual neural processing are conducted by separate populations of neurons and that neural representation may be quite different between these two important surface attributes.

6 Conclusion and Future Problems

We speculate that visual features distinguishing surface glosses are detected in early visual areas and that this information is integrated along the ventral visual pathway to form neural representation of a variety of glosses of object images in the IT cortex. Neural mechanisms underlying discrimination between ‘Gold’ and ‘Yellow’ should at least in part lie in this process. Both color and gloss information are represented in the IT cortex, and discrimination between ‘Gold’ and ‘Yellow’ may be achieved by combining these information in the IT cortex. However, many important questions remain to be answered. What features in the visual images are used to discriminate a variety of gloss, how are they detected in the early visual areas and how are they integrated in the ventral visual pathway to form neurons selective for gloss? Finally, although gold perception is commonly associated with glossy objects, there are examples in which objects that do not have clear highlights appear golden [29]. Whether the common neural mechanisms are used for different kinds of gold perception is also an open question for future research.

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