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学 位 論 文 題 目	Neural Selectivity and Representation of Gloss in the Monkey Inferior Temporal Cortex
論 文 審 査 委 員	主　　査　　教授　伊佐　正 教授　小松　英彦 教授　吉村　由美子 教授　大澤　五住　大阪大学

論文内容の要旨

Only from visual information, we can easily recognize whether an object is made of plastic or metal, or whether surface condition is slippery or not. How can we recognize material and surface condition of objects? Objects have specific surface reflectance properties that depend on the materials and fine structures of the surface. Surface gloss provides important information on the material composition of an object and the fine structure of its surface. Although gloss perception is very important for object recognition, little is known about the neural mechanisms related to gloss perception.

To study how gloss is represented in the visual cortical areas related to object recognition, the author conducted single unit recording experiment to study neural selectivity and representation of gloss in the inferior temporal cortex of awake macaque monkeys performing a visual fixation task. In the first part of the experiment, the author examined the relationship between neural responses and physical parameters related to gloss, and in the second part, the author examined the relationship between neural responses and perceptual parameters related to gloss. In the first part of the experiment, the author examined the responses of neurons to a set of object images having various combinations of specular reflection, diffuse reflection and roughness that are important physical parameters of surface gloss (gloss stimulus set). The author found that there exist neurons in the lower bank of the superior temporal sulcus in IT cortex that selectively responded to specific combination of surface reflectance parameters. The author recorded the activities of 215 neurons that responded to the gloss stimulus set, and of these, 193 neurons exhibited selectivity to the gloss parameters.

However, the author has to exclude the possibility that the selectivity is due to image features not particularly related to gloss. Images in the gloss stimulus set varied with respect to their local luminance pattern; that is, glossy stimuli have sharp light spots corresponding to highlights. It was therefore possible that these selective responses were due to the presence of a specific pattern of highlights in some stimuli. To test this possibility, the author recorded the responses of the same neurons to the gloss stimulus set rendered on a different 3D shape and assessed whether the change in shape affected stimulus selectivity. In this manipulation, the local luminance pattern changed but perceived glossiness was maintained. Therefore, if the selectivity to gloss stimulus set is due to local image features, selectivity will change when 3D shape is changed. On the other hand, if the selectivity reflected the differences in the glossiness, selectivity will be maintained. Images in the gloss stimulus set also varied with respect to the mean chromaticity and luminance. It was therefore possible that the selectivity to gloss stimulus set was due to differences in the color and luminance of the stimuli. To test this possibility, the author tested the responses to stimuli in which the pixels were randomly rearranged within the object contour (shuffled stimuli). In this manipulation, average color and luminance were not changed but perceived glossiness was dramatically changed. Therefore, if the selectivity is due to the differences in the average color and luminance, selectivity will not change when the pixels are randomly rearranged. On the other hand, if the selectivity related to the glossiness, it should significantly change. The author conducted these two sets of control experiments using stimuli with different shape as well as shuffled stimuli in 139 out of 193 neurons that exhibited selectivity to the gloss parameters. The author defined neurons as gloss-selective (gloss-selective neurons) based on the following two criterions. The first criterion is that there was significant correlation between the response to the original shape and those to a different shape. The second criterion is that either the neuron did not show significant response to the shuffled stimuli (<10 spikes/s and/or $p > 0.05$, t-test) or the correlation between the patterns of stimulus selectivity obtained by stimuli with the original shape and the shuffled stimuli were not significant. Of the 139 neurons tested in these two control tests, 57 neurons satisfied both of these two criteria, and were regarded as gloss-selective neurons.

Illumination is another important factor involved in the image formation, and the author has examined the effect of the change in illumination for 48 gloss-selective neurons. When the author compared the responses to the gloss stimulus set rendered under default natural illumination and those to the stimuli rendered under another natural illumination, 40 out of 48 gloss-selective neurons exhibited significant correlation between the two sets of responses. This result is consistent with the expectation that the selectivity of these neurons will be maintained because it has been shown that changing the illumination environment does not affect the apparent glossiness very much, as long as natural illumination is used, and confirms that gloss selectivity of gloss selective neurons is largely independent of a change in illumination.

The stimulus preference of gloss-selective neurons differed from cell to cell and, as a population, responses of gloss-selective neurons covered the entire region of the gloss space though there was a tendency for glossier stimuli to elicit stronger responses. In order to understand how different glosses are represented by the activities of population of gloss-selective neurons, the author conducted multidimensional scaling (MDS) analysis using the neural distance between each stimulus pair. The results of MDS analysis showed that the population responses of gloss-selective neurons systematically represent a variety of gloss.

In the second part of the experiment, in order to understand how the responses of gloss selective neurons are related to perceived gloss, responses of gloss selective neurons were mapped in perceptual gloss space in which glossiness changes uniformly. The author found that responses of most gloss selective neurons could be explained by linear combinations of two parameters that are shown to be important for gloss perception. This result indicates that the responses of gloss-selective neurons and gloss perception are characterized by common parameters, and this suggests that the responses of gloss selective neurons are closely related to gloss perception. The author concludes that in the visual cortex there exist some mechanisms to integrate local image features and extract information about surface gloss, and that this information is systematically represented in the IT cortex that plays an important role in object recognition.

博士論文の審査結果の要旨

視覚的な物体認識において、物体がどのような素材で出来ているか、硬いのか柔らかいのか、つるつるの表面なのかざらざらした表面なのか、といった情報はきわめて重要である。光沢は素材や物体の表面状態を認識する上で重要な手がかりであり、光沢知覚のメカニズムに関する心理物理学研究は盛んに行われている(Motoyoshi et al. 2007)ものの、神経科学的な研究は少なく、その基盤となる神経メカニズムはほとんど分かっていない。そこで出願者はは物体表面の光沢情報が脳内でどのように処理されているかを明らかにするために以下の実験を行った。光沢知覚の神経メカニズムを解明するために、第1実験では光沢情報を表現している細胞が存在するかどうか調べ、第2実験では知覚的な光沢と神経活動の関係を調べた。記録場所は下側頭皮質（IT）の上側頭溝下壁で、物体の3次元形状に選択的な細胞などが存在することが報告されている領野である(Yamane et al. 2009)。注視課題を行っているニホンザルの頭頂部から微小電極を脳内に刺入して記録を行い、注視期間中に呈示した視覚刺激に対する細胞の応答を調べた。

第1実験では様々な光沢を持つ視覚刺激を作成する為に、MERL BRDF データベースから33個のできるだけ見かけの違う表面反射特性を選び、それらのWard-Duer モデルのパラメータ（拡散反射率，鏡面反射率，ラフネス）を用いた。実験の結果、33個の光沢刺激セットの特定の刺激に対して選択的に反応する細胞が存在することが分かった。その選択性は形状を変化させても反応の選択性が変わらず、一方で物体画像をピクセル毎にランダムに再配置すると選択性が変化した。形状を変化させると局所的な画像特徴（ハイライトによる色や形など）は変化するものの光沢は変化しないのに対し、ピクセル毎にランダマイズした刺激では、平均輝度や色などは変わらないが光沢知覚は劇的に変わることから、これらのIT細胞は局所的な画像特徴や平均的な輝度/色ではなく光沢に反応していると考えられる。また多変量解析の結果、これらの細胞集団の活動は、異なる光沢を規則的に表現していることが分かった。これらの結果は下側頭皮質に物体の光沢を表現する細胞が存在することを示唆している。

第2実験では、これらの細胞の反応と知覚的な光沢との関係を調べるために、知覚的な光沢が均一に変化する光沢空間(Ferwerda et al. 2001)に基づいて実験を行った。この光沢空間はc軸とd軸の2軸からなっており、この空間上を均等に変化させたパラメータを用いて作成した刺激に対する光沢選択的細胞の反応を調べた。その結果、光沢選択性細胞の反応は光沢空間上で系統的に変化し、ほとんどの光沢選択性細胞の反応は光沢知覚に重要であるc軸とd軸の線形な組み合わせによって説明できることが分かった。これは光沢選択性細胞の反応が知覚的な光沢と密接に関わっていることを示している。

上記の成果は、光沢知覚の脳内メカニズムという比較的新しい研究領域に先進的に取り組み、その基盤となる知見を与えるものであり、新規性が高く、研究としての完成度も高い。従って本論文は学位に値すると認める。