別紙４－１（課程博士（英文））

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Abstract（Doctor）

Title of Thesis	Image cues for perceiving depth of transparent and reflective objects

Approx. 800 words

Perceiving the shape of objects in depth is an essential visual function in daily life. The human visual system tries to decompose a retinal image into the experiences of shape, motion (if it exists), illumination, and surface optics. However, this process is not always perfect, especially when no binocular cue is given, because this decomposition is an ill-posed problem. For this problem, a mis-perception of shape sometimes accompanies the mis-perception of a surface's optics, such as glossiness and albedo. It is also known that perceived depth of objects is modulated by the surface's optics. These complicated interactions between the shape and surface optics of objects is not an inherent perceptual error of the visual system, but rather, indicates the perceptual inference that is most likely occur. Recent studies have found those mis-perception associated with specular reflectance is still poorly understood in other important optical properties – transparency. Here, I focused on two important surface optics; specularity and transparency and examined how these optical properties affect human perception of three-dimensional shape. If some biases exist in perception, I ask what image features could explain any resulting depth perception.

Firstly, I examined how the human observers estimate the depth of the three-dimensional objects which were simulated to have different materials by using computer graphics. The rendered objects varied in the thickness, bumpiness, motion, transparency, specular reflectivity under photorealistic lightning environments. Observers were asked to rate the overall convexity of these objects along the depth axis. The results showed that observers perceived solid purely transparent objects as flatter than the same objects rendered with opaque (matte or specular) reflectance properties. These results were consistent across changes in thickness, bumpiness, lighting environments, and dynamic/static stimulus presentations.

Secondly, I tested how the relative intensity of specular reflection to the transparent objects affect depth perception. In the previous experiment, I found that the stimulus image of 50% specular and 50% transparent objects induced similar depth perception to the 100% specular objects. Thus, it is important to know which ratio of specular reflection contributes to a threshold change depth perception. In this experiment, various ratios of specular

reflections of transparent objects were presented. The observers compared the overall thickness along the depth axis of the transparent objects with a textured matte object. The results showed that adding only a small ratio (< 5%) of specular reflection to the refractive component was required for equating perceived thickness in depth of the matte object, and the ratio was almost equal to the specular ratio of the ordinary glass and ice. However, this specular ratio was very different across the light fields, indicating that the structure of illumination significantly biased the perceived shape of shiny transparent objects relative to matte opaque objects.

Finally, I investigated what image cues explaining those observed depth perceptions. Across the models I tested, a regional variation in local root-mean-square (vRMS) contrast of the image was shown to provide good prediction of perceived depth of the objects. The vRMS contrast is a simple second-order image statistic, and thus easy to compute from the image and maybe implementable in the human visual system. I also showed that the vRMS contrast could be applicable to shapes other than a perfect sphere.

The finding of underestimation of the perceived depth of the transparent objects, along with the overestimation of the specular objects, is particularly important in the field of material perception. Many studies of material perception have focused on the perception of the material itself, such as glossiness (related to reflective light) and transparency (related to refractive light). In my study however, I examined how shape perception was modulated by reflective/refractive optical properties. This experimental paradigm used in my study is also applicable to other material properties, including semi-transparency, chromaticity, and other complex materials.

It was also shown that perceived depth can be explained by vRMS contrast regardless of the materials, including matte, glossy, and transparent materials. Thus, many complex surfaces could be reproduced by combining relevant image-based information together. Although further examination of the model and perception is needed, the model of vRMS contrast would be helpful for industry applications that need to control the appearance of products. If the industry stakeholder wants to modify the appearance of the shape by changing surface coating and printing, the vRMS contrast model could be a good index to this end.