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Visual categorization of surface qualities of materials by capuchin monkeys and humans

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ABSTRACT

Visually identifying and categorizing the material composition of objects before actually interacting with them is an important skill for operating smoothly and safely in the world. This ability is assumed to have been shaped by evolution; therefore, non-human animals should share similar categorization abilities. Little is known, however, about how non-human animals do this. We tested whether tufted capuchin monkeys (*Cebus apella*) were able to visually categorize images that represented nine different materials (metal, ceramic, glass, stone, bark, wood, leather, fabric, and fur), and we compared their performance with that of humans. Capuchins showed excellent categorization abilities for images of fur, which is a familiar material to captive monkeys. Humans showed a tendency to confuse material categories that resembled each other visually and/or semantically. Correlation analyses on reaction time showed that both species made correct choices rapidly in selecting glossy categories like metal and ceramic compared with matte categories like fabric and stone, which contain minute patterns. Overall, our results suggest that monkeys share similar perceptual tendencies with humans in visual categorization of material images to some extent and the potential to categorize materials frequently encountered in their daily lives by visual observation.

1. Introduction

We routinely classify and identify the material composition of objects visually on the basis of their distinctive surface qualities, which are formed by the reflection of light on the materials. Material categories vary from natural (e.g., wood and stone) to artificial (e.g., metal and glass), and some category names refer to surfaces of animals (e.g., fur and leather). Visual recognition of materials facilitates proper and adaptive action with their objects. Progress has been made in understanding the perception of surface qualities of materials in humans (Anderson, 2011; Maloney & Brainard, 2010; Motoyoshi, Nishida, Sharan, & Adelson, 2007; Sharan, Rosenholtz, & Adelson, 2014). Sharan and colleagues demonstrated that material categorization is as rapid and accurate as object and scene categorization and one of a basic abilities of the visual system (Sharan et al., 2014). Another study (Wolfe & Myers, 2010), using visual search based on surface qualities of materials, showed that materials cannot draw attention automatically. An investigation of the semantic aspects of materials showed that humans represent material classes similarly in the visual and semantic domains (Fleming, Wiebel, & Gegenfurtner, 2013).

From a biological point of view, our perception of materials should have been shaped largely through evolutionary processes. Arguably, visual perception of the surface qualities of materials is extremely useful for survival among diurnal animals that use vision as the primary sensory modality. For example, perceiving surface qualities such as glossiness and transparency should be helpful for identifying fresh fruits and water, especially when other cues such as color or odor are unreliable.

The ecological importance and evolutionary foundation of the perception of surface qualities have received recent support from several physiological studies. Neurophysiological studies have found neurons and brain areas responsive to surface qualities, such as glossiness and texture, in monkey brains (Freeman, Ziemba, Heeger, Simoncelli, & Movshon, 2013; Nishio, Goda, & Komatsu, 2012; Nishio, Shimokawa, Goda, & Komatsu, 2014; Okazawa, Goda, & Komatsu, 2012; Okazawa, Tajima, & Komatsu, 2015). An fMRI study reported that macaque brains represent real-world material categories (e.g., metal, wood, fur) in a way similar to humans (Goda, Tachibana, Okazawa, & Komatsu, 2014). These studies suggest that primates may share a similar perception of surface qualities of materials. Although experience ought to modify material perception, more fundamental processes are likely to have

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considerable evolutionary origin. However, few studies have asked how non-human animals perceive materials, and therefore very little information is available to discuss evolutionary backgrounds of such perception.

In the present study, we aimed to investigate how non-human primates visually perceive and categorize materials humans encounter in daily life. We tested this ability in tufted capuchin monkeys (*Cebus apella*), a species of New World monkeys that separated from Old World monkeys about 40 million years ago (Kiesling, Yi, Xu, Sperone, & Wildman, 2014). Although capuchin monkeys are phylogenetically more distant from humans than are Old World monkeys such as macaques, they show habitual tool-using behavior such as cracking nuts with stones (Ottoni & Izar, 2008) and use visual information effectively to conduct various tasks (Paukner, Huntsberry, & Suomi, 2009; Wright, 1999). They also show remarkable omnivorous tendency; feed on small-sized species of amphibians and reptiles, young birds and birds' eggs, as well as various kinds of fruit and insects (Izawa, 1975, 1978). Therefore, they may benefit from recognizing materials such as stones and textures of foods with cryptic coloration visually. They share many perceptual properties with humans (e.g., preference for regularity, perceptual completion) (Anderson, Kuwahata, Kuroshima, Leighty, & Fujita, 2005; Fujita & Giersch, 2005), but a difference has also been detected (e.g., perceptual grouping) (Spinozzi, De Lillo, & Castelli, 2004). Because of moderate similarity and differences between two species, they are good candidates to compare visual material perception from an evolutionary perspective. In this study, we observed how similarly (or differently) monkeys and humans behave in visual matching task based on material properties and discussed what kind of factors, e.g., visual features, saliency and experience, influence their performance. The comparison between the two species would shed light on the evolutionary processes of material perception in primates.

2. Experiment 1

2.1. Methods

2.1.1. Animal subjects

The animal care and experiment were conducted according to the principles of the ARRIVE (Animal Research: Reporting of In Vivo Experiments) guidelines (Kilkenny, Browne, Cuthill, Emerson, & Altman, 2010). Seven tufted capuchin monkeys participated in the experiment. Among them, two 2-year-old females conducted experimental design 1 (see experimental design). They had been trained to match to sample using simple shapes (circle and cross) for 1 year but had never experienced experiments on visual perception before the training. Other five adult monkeys (8–18 years old, three females) conducted experimental design 2. They had experienced various types of visual and cognitive experiments (Fujita, 2009; Fujita & Giersch, 2005) with touch-sensitive monitors and were highly skilled at matching-to-sample tasks. The monkeys were not food deprived but received a portion of their daily diet during testing and the remainder in their home cage after testing each day. In the home cage, monkeys had free access to water. No animals were sacrificed in this study. The experiment was approved by the Animal Experiments Committee of the Graduate School of Letters, Kyoto University (permit number 11-04) in accordance with the European Directive 2010/63 on the Protection of Animals in Scientific Experimentation.

2.1.2. Stimuli and apparatus

We used material images created by the computer graphics software LightWave 3D (NewTek, San Antonio, TX, USA). The images were of nine material categories (metal, ceramic, glass, stone, bark, wood, leather, fabric, and fur; Fig. 1A). Each category had eight exemplars with different surfaces and slightly different meaningless shapes (shapes one to eight). In total, there were 72 gray-scale material images (Fig. S1). A color version of these images was used in the previous fMRI study with human subjects (Hiramatsu, Goda, & Komatsu, 2011). The psychological analysis in the previous study showed that exemplars of metal, ceramic and glass share glossy appearance and those of other categories share matte appearance (Hiramatsu et al., 2011). Because capuchin monkeys are known to have highly polymorphic color vision (Jacobs, 2007), we used gray-scale images in our experiments to eliminate the effect of color-vision differences. All images in the current study were resized to 180 × 180 pixels (ca. 9.5 × 9.5° at a 15-cm viewing distance). The images were presented on a touch-sensitive LCD monitor (TSD-CT157-MN; Mitsubishi, Japan) (1024 × 768 pixels). The image presentation, response detection, and food delivery were controlled by a custom program written with Visual Basic 2008 programing software (Microsoft, Redmond, WA, USA) installed on a built-to-order computer (CPU: Core 2 Duo 2.93 GHz; Intel, Santa Clara, CA, USA). The monitor was calibrated with the i1 Display Pro calibration tool (X-rite, Grand Rapids, MI, USA). The background of the material images was uniformly gray ($x = 0.311$ and $y = 0.330$, 30 cd/m^2). The monitor was placed at the front of a transparent operant box (45 × 45 × 45 cm) where the monkeys performed the tasks. The experiment was conducted in a dark room with low illumination by an incandescent bulb (7 lux at monitor location) attached to the operant box. White noise was presented during the experiment so that monkeys were not disturbed by noise from outside the operant box.

2.1.3. Experimental design

The experiments asked whether monkeys would generalize the identity-matching performance learned in training phases to similar images in test phases. There were two types of test trials: identity matching and category matching. Performance of identity matching would indicate the ability to directly apply the strategy learned in training phases. In contrast, performance of category matching would imply the ability to generalize the learned concept to slightly different images that share similar surface qualities, i.e. material category.

Briefly, trials started with the monkey's pressing a lever down for 1 s, which resulted in appearance of a sample image. After the monkey touched the sample image three times, nine comparison images, one exemplar from each category, appeared (Fig. 1B). Trials ended when the monkey touched one of the comparison images. More details are described in Supplementary methods.

We used two experimental designs (designs 1 and 2). Fig. 1C summarizes each experimental design. The design 1 consisted of five phases. The first two phases were training, in which the monkeys had to choose the same image as the sample from nine comparison images (identity matching) that consisted of a stimulus set to which the sample image belong. Two stimulus sets were used for the first and second training phases, respectively (shapes one to four). The third phase consisted of baseline and test trials. The baseline trials were identity matching with learned images in the first and second phases. In the test trials, new stimulus images from four stimulus sets, shapes five to eight, were used. There were two types of test trials: identity matching and category matching. In identity matching, comparison images comprised of a stimulus set that contained one image identical to the sample. In category matching, comparison images were chosen from a different stimulus set that consisted of nine images belonging to different material categories but sharing the same shape. The correct answer in a category matching trial was to choose a comparison with the same category to the sample but with a different material texture