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Curious monkeys have increased gray matter density in the precuneus

Kimberley A. Phillips[a,b,*], Francys Subiaul[c], Chet C. Sherwood[d]

[a] Department of Psychology, Trinity University, San Antonio, TX 78212, United States
[b] Southwest National Primate Research Center, Texas Biomedical Research Institute, San Antonio, TX, United States
[c] Department of Speech and Hearing Science, The George Washington University, Washington, DC 20052, United States
[d] Department of Anthropology, Center for the Advanced Study of Hominid Paleobiology, The George Washington University, Washington, DC 20052, United States

HIGHLIGHTS

- We examine the neural correlates of curiosity.
- Curious monkeys had a greater density of gray matter in the precuneus.
- The precuneus is associated with integrated tasks such as memory and self-awareness.
- Monitoring self-awareness may play a role in cognitive processes mediating curiosity.

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ABSTRACT

Curiosity is a cornerstone of cognition that has the potential to lead to innovations and increase the behavioral repertoire of individuals. A defining characteristic of curiosity is inquisitiveness directed toward novel objects. Species differences in innovative behavior and inquisitiveness have been linked to social complexity and neocortical size [18]. In this study, we observed behavioral actions among nine socially reared and socially housed capuchin monkeys in response to an unfamiliar object, a paradigm widely employed as a means to assess curiosity. *K*-means hierarchical clustering analysis of the behavioral responses revealed three monkeys engaged in significantly more exploratory behavior of the novel object than other monkeys. Using voxel-based-morphometry analysis of MRIs obtained from these same subjects, we demonstrated that the more curious monkeys had significantly greater gray matter density in the precuneus, a cortical region involved in highly integrated processes including memory and self-awareness. These results linking variation in precuneus gray matter volume to exploratory behavior suggest that monitoring states of self-awareness may play a role in cognitive processes mediating individual curiosity.

1. Introduction

Curiosity is the desire to learn about what is unknown. Montgomery [15,16] postulated that human and animal behavior is often motivated by such self-enrichment tendencies. His approach-avoidance theory maintained that curiosity is a balance between two motivations—the drive to explore and the fear resulting from the novel situation. Berlyne [5] considered curiosity to be a motivational drive, and a prerequisite for exploratory behavior. The motivation for curiosity is unique from other drives in that it is aroused not by an internal state in the individual, but rather by a novel external stimulus. This motivation is also satiated quickly with continuous exposure to the stimulus.

Curiosity and exploratory behavior are intertwined and as such, difficult to define independently; both terms are used to refer to behavior that provides a gain in information about the environment.

The neurobiology underlying curiosity remains poorly understood. In humans, curiosity has been linked to functional activation in the inferior frontal gyrus (Broca's area) and the caudate nucleus, associated with anticipated reward [13]. Dopaminergic receptors in the dentate gyrus are associated with the generation of exploratory behavior in mice [20]; these receptors also play a role in learning and memory.

Here, we characterized behavioral responses among nine socially reared and socially housed capuchin monkeys to a novel object, a paradigm widely employed as a means to assess curiosity [8,17,25]. Additionally, we obtained high-resolution T1-weighted structural magnetic resonance images of the brain from these same monkeys, to relate neuroanatomical differences to their behavior.

* Corresponding author at: Department of Psychology, Trinity University, One Trinity Place, San Antonio, TX 78212, United States. Tel.: +1 210 999 7102; fax: +1 210 999 8386.
E-mail address: Kimberley.Phillips@Trinity.edu (K.A. Phillips).

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Fig. 1. Still images illustrating an individual monkey engaging in tactile exploration (a) and olfactory and visual exploration (b).

2. Materials and method

2.1. Subjects

Nine adult capuchin monkeys (*Cebus apella*) were used in this study, including five males and four females ranging in age from 5 to 23 years (M = 13.4 years, SD = 6.6 years). Subjects were socially housed in enriched environments with perches, swings, and fresh browse. The social composition of this group closely resembled that of wild groups; furthermore, normative capuchin social behavior–including grooming and playing—was regularly displayed. New World Monkey Chow and water were available *ad libitum*; fruit was provided once a day. This study was carried out in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health and was approved by the Institutional Animal Care and Use Committee, Hiram College, Hiram Ohio, USA.

2.2. Behavioral testing

All subjects were removed from the social group and tested individually in a separate enclosure (1.5 m × 1.5 m × 2.4 m), without a human present. All were familiar with the enclosure from participation in a prior experiment on prey capture behavior [10]. Monkeys remained in the enclosure for 5 min, where they had no auditory or visual contact with other monkeys or humans. Behavioral responses were scored from video recordings made of the testing session. The enclosure had a Plexiglas panel on the front portion through which unobstructed visual access was provided. Before a trial began, a brightly colored, novel object was hung on a wall on the inside of the enclosure (Developlay Activity Center by Tiny Love). This children's toy has several objects that can be manipulated through pulling, pushing, turning, *etc.* Different textures, sounds, and colors enhance the novelty and feedback responsiveness of the object. A perch was positioned beneath the object to provide access to subjects.

A video camera was positioned on a tripod to provide an unobstructed view of the perch and object. A trial began once a subject was transferred into the testing enclosure. During trials, the experimenter was not in the room and was no longer in visual or auditory contact with the subject. The subject was allowed to explore the novel object for 5 min. After 5 min the experimenter returned to the room and turned off the video camera; the subject was transferred out of the testing enclosure and returned to the social group. Each subject received one trial.

2.3. Image acquisition

Structural MRIs of the brain were obtained from subjects separately from the behavioral testing session. In order to obtain the noninvasive MRI images required for this study, the subject's head needed to be immobile during the scan. Therefore, the capuchins were anesthetized for the procedure. Anesthesia was used only for the purpose of restraint during collection of the brain images. Subjects remained anesthetized throughout the MRI procedure and respiration rate, heart rate, and oxygen consumption were continually monitored by a veterinarian.

In vivo structural magnetic resonance scans were obtained for all subjects on a Siemens 3.0 Tesla Scanner at the Neuroscience Imaging Center in Pittsburgh, PA. Subjects were initially immobilized by ketamine (7 mg/kg) and meditomidine (0.06 mg/kg) injection and subsequently anesthetized with propofol (250–350 μg/kg/min). Subjects were then placed into the scanner chamber and their heads were fitted inside a 12 cm head coil. High-resolution (isotropic 0.5 mm) T1-weighted 3D MPRAGE scans were acquired (TR = 1500 ms, TE = 3.04 ms, no echo-train, number of signals averaged = 3, matrix size = 256 × 256). Scan acquisition time was approximately 50 min. After completing the MRI procedure subjects were allowed to recover from the effects of anesthesia before return transport.

Prior to analysis, data were converted into the Nifti file format. Nifti files for individual subjects were numerically coded prior to analysis to prevent observer bias.

3. Results

Video recordings of the test session were scored by an individual who was unfamiliar with the subjects. The following data were