REFERENCES

1. Murase, K., Moriwaki, Y., Mori, T., Liu, X., Masaka, C., Takada, Y., Maesaki, R., Mishima, M., Fujii, S., Hirano, Y., and Kawabe, Z. (2020). Mechanism of self/nonself-discrimination in Brassica self-incompatibility. Nat. Commun. *11*, 4916.

2. Abhinandan, K., Sankaranarayanan, S., Macgregor, S., Goring, D.R., and Samuel, M.A. (2022). Cell–cell signaling during the Brassicaceae self-incompatibility response. Trends Plant Sci. *27*, 472–487.

3. Hiscock, S.J., and Dickinson, H.G. (1993). Unilateral incompatibility within the Brassicaceae: further evidence for the involvement of the self-incompatibility (S)-locus. Theoret. Appl. Genet. *86*, 744–753.

4. Hiscock, S.J., and Tabah, D.A. (2003). The different mechanisms of sporophytic self–incompatibility. Philos. Trans. R. Soc. Lond. B Biol. Sci. *358*, 1037–1045.

5. Kakita, M., Murase, K., Iwano, M., Matsumoto, T., Watanabe, M., Shiba, H., Isogai, A., and Takayama, S. (2007). Two distinct forms of M-locus protein kinase localize to the plasma membrane and interact directly with S-locus receptor kinase to transduce self-incompatibility signaling in *Brassica rapa*. Plant Cell *19*, 3961–3973.

6. Stone, S.L., Arnoldo, M., and Goring, D.R. (1999). A breakdown of Brassica self-incompatibility in ARC1 antisense transgenic plants. Science *286*, 1729–1731.

7. Abhinandan, K., Hickerson, N.M., Lan, X., and Samuel, M.A. (2022). Disabling of ARC1 through CRISPR/CAS9 leads to a complete breakdown of self-incompatibility responses in Brassica napus. Plant Commun. *4*, 100504.

8. Samuel, M.A., Chong, Y.T., Haasen, K.E., Aldea-Brydges, M.G., Stone, S.L., and Goring, D.R. (2009). Cellular pathways regulating responses to compatible and self-incompatible pollen in Brassica and Arabidopsis stigmas intersect at Exo70A1, a putative component of the exocyst complex. Plant Cell *21*, 2655–2671.

9. Sankaranarayanan, S., Jamshed, M., and Samuel, M.A. (2015). Degradation of glyoxalase I in Brassica napus stigma leads to self-incompatibility response. Nat. Plants *1*, 15185.

10. Scandola, S., and Samuel, M.A. (2019). A flower-specific phospholipase D is a stigmatic compatibility factor targeted by the self-incompatibility response in Brassica napus. Curr. Biol. *29*, 506–512.e4.

11. Zhang, L., Huang, J., Su, S., Wei, X., Yang, L., Zhao, H., Yu, J., Wang, J., Hui, J., Hao, S., and Song, S. (2021). FERONIA receptor kinase-regulated reactive oxygen species mediate self-incompatibility in Brassica rapa. Curr. Biol. *31*, 3004–3016.e4.

12. Singh, R., Singh, S., Parihar, P., Mishra, R.K., Tripathi, D.K., Singh, V.P., Chauhan, D.K., and Prasad, S.M. (2016). Reactive oxygen species (ROS): beneficial companions of plants' developmental processes. Front. Plant Sci. *7*, 1299.

13. Dumanović, J., Nepovimova, E., Natić, M., Kuča, K., and Jaćević, V. (2021). The significance of reactive oxygen species and antioxidant defense system in plants: A concise overview. Front. Plant Sci. *11*, 552969.

14. Liu, C., Shen, L., Xiao, Y., Vyshedsky, D., Peng, C., Sun, X., Liu, Z., Cheng, L., Zhang, H., Han, Z., and Chai, J. (2021). Pollen PCP-B peptides unlock a stigma peptide–receptor kinase gating mechanism for pollination. Science *372*, 171–175.

15. Huang, J., Yang, L., Yang, L., Wu, X., Cui, X., Zhang, L., Hui, J., Zhao, Y., Yang, H., Liu, S., and Xu, Q. (2023). Stigma receptors control intraspecies and interspecies barriers in Brassicaceae. Nature *614*, 303–308.

16. Giranton, J.L., Dumas, C., Cock, J.M., and Gaude, T. (2000). The integral membrane S-locus receptor kinase of Brassica has serine/threonine kinase activity in a membranous environment and spontaneously forms oligomers in planta. Proc. Natl. Acad. Sci. USA *97*, 3759–3764.

Comparative cognition: Capuchin monkeys believe in magic

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Capuchin monkeys are unique among New World monkeys for their manual dexterity and use of tools. New research using magical sleight of hand shows visual perception of others' actions paralleling their manual skills.

In the 19th and early 20th centuries, the organ grinder was a familiar — if not always welcome — presence in European and American cities. These street musicians were frequently accompanied by capuchin monkeys, who would perform tricks and collect coins from spectators, as depicted in Norman Rockwell's painting from 1920 (Figure 1). The use of capuchin monkeys was no accident. Among the New World monkeys, capuchins from the genera *Cebus* and *Sapajus* are unique in the dextrous use of their hands[1], for example in their ability to make precision grips with their thumb and fingers[2], and their use[3] and manufacture[4] of tools. These abilities are particularly striking as they appear to have evolved independently of comparable abilities in Old World monkeys such as macaques and apes, including humans.

These dextrous manual behaviours are reflected in the anatomy of the monkey's hand itself. A range of anatomical features differentiate the hands of capuchin monkeys from closely related New World monkeys, including the depth of the carpal tunnel in the wrist and the degree of flexion allowed by the carpal–metacarpal joint of the thumb[5]. These features allow the capuchin to use at least a form of pseudo-opposability of the thumb, if not the perfect thumb-index opposition seen in humans. Importantly, these anatomical specialisations of the hand are paralleled by specialisations of the nervous system. These include overall expansion of the

size of the cerebral cortex[6], the emergence of somatosensory area 2[7], expansion of the posterior parietal cortex[8], and the presence of direct cortico-motoneuronal projections within the corticospinal tract[9,10], a feature closely linked to fine manual dexterity in Old World monkeys, apes, and humans.

The dextrous manual behaviours of capuchin monkeys are well-established. It remains unclear, however, what implications these have for these animals' perception of the world, for instance how they perceive actions performed by other monkeys or people. Research in human infants has found that the perceptual interpretation of seen reaches of other people changes depending on the infant's own experience in producing similar reaches[11]. There is suggestive evidence that the same may be true in capuchin monkeys. For example, they look longer at actions performed by a human that they have experience performing themselves[12]. The unique manual abilities of capuchins among the New World monkeys, however, also suggest that they may perceive actions differently than other monkeys who do not have these abilities. In a new study published in this issue of *Current Biology*, Garcia-Pelegrin *et al.*[13] investigated this question by asking whether monkeys are fooled by magic tricks.

Magic tricks have been a source of entertainment for centuries. Increasingly, however, they are also being used as scientific tools[14]. Recent research has used magic tricks to probe perceptual and cognitive processes in both humans[15] and animals[16]. The logic of this approach is that magic tricks frequently work by exploiting fundamental mechanisms of human perception and attention, for example mechanisms underlying predictive extrapolation of object motion or automatic attentional cueing from social signals such as eye gaze. In the famous *Le Tourniquet*, or *French drop* trick, the magician holds a coin in their left hand and grabs the coin with the thumb and fingers of the right hand. A little wave, maybe a light blow on the fingers and — abracadabra — the coin has vanished! However, (SPOILER ALERT) the coin has not really vanished. Instead, the magician has used sleight of hand to let the coin drop into the palm of their left hand. The trick is effective because human viewers have strong expectations that the movements of a precision grip directed towards an object result in that object being grasped.

Figure 1. Manual dexterity in capuchin monkeys.
Norman Rockwell's (1920) painting *The Organ Grinder* shows a capuchin monkey using its dextrous manual abilities to collect coins from an audience.

Garcia-Pelegrin *et al.*[13] presented the French drop trick to three species of New World monkey, yellow-breasted capuchins (*Sapajus xanthosternos*), and two species with less manual dexterity, common marmosets (*Callithrix jacchus*), and Humboldt's squirrel monkeys (*Saimiri cassiquiarensis*). A human experimenter showed the monkey a food reward, performed the French drop, and then allowed the monkey to choose one of the two hands. A monkey who is fooled by the trick should search in the wrong hand, whereas one who is not fooled should find the reward. Like humans, capuchin monkeys — who are able to produce the precision grip at the core of the trick — were highly susceptible, searching for food in the wrong hand 81% of the time. In striking contrast, marmosets — who are not able to perform a precision grip — were fooled only 6% of the time.

If marmosets' insensitivity to the trick is related to their inability to produce the seen precision grip movement, then they should become sensitive if the trick is modified to reflect their motor repertoire. Garcia-Pelegrin *et al.*[13] tested this by presenting a variation on the French drop in which a whole-hand power grip is used to (apparently) grasp the coin. Unlike the precision grip, all the monkeys tested can and do use power grips regularly. Remarkably, both capuchins and marmosets were susceptible to the power grip variant of the trick, being fooled 81% and 94% of the time, respectively.

These results show a striking correspondence between the monkey's own manual abilities and their

interpretation of the seen action of the human experimenter. Capuchin monkeys — who produce both precision and power grips — are fooled by the French drop trick performed both with precision and power grips. Marmosets — who produce power, but not precision, grips — are fooled only by the power grip variant of the trick.

One complication of the results concerned squirrel monkeys. Unlike capuchins, squirrel monkeys do not regularly use precision grips[2] and their thumb lacks the specialisations that facilitate precision grips in capuchins[5]. However, their thumbs do have a degree of pseudo-opposability against the side of the index finger that is lacking in marmosets, and there have been reports of tool use by these animals[17]. This makes the hand dexterity of squirrel monkeys interestingly intermediate between marmosets and capuchin monkeys. Contrary to Garcia-Pelegrin *et al.*'s[13] predictions, squirrel monkeys behaved similar to capuchins in all tasks. This shows that they are fooled by the seen precision grip, despite not being able to perform this action themselves, at least not in quite the same way as the human magician. This result challenges any simple interpretation of the link between action ability and action perception. It may be that seen actions are coded at a level of abstraction in which even the approximate match between the pseudo-opposable movements of the squirrel monkey's hand and the full precision grasp of the human magician is sufficient.

Of course, the immediate causes of monkeys being fooled by the French drop lie not in their hands, but in their brains. Garcia-Pelegrin *et al.*'s study[13] focused on behaviour, but it will be important in future research to investigate the neural mechanisms of these effects using neurophysiological or neuroimaging methods. While the brain areas involved are not known, a likely target is the posterior parietal cortex, particularly the region around the intraparietal sulcus. Comparative MRI studies of brain structure have shown massive expansion of this region in capuchin monkeys in which it is as much as 16 times larger than the homologous region in marmosets[8]. It is also a region known to be involved in both action production and action perception in both Old World macaque monkeys[18] and humans[19]. Finally, the suggestion discussed in the previous paragraph that the link between action and perception may occur at a high level of abstraction may also implicate the posterior parietal cortex, which sits at the top level of the hierarchy of motor abstraction[20].

The results of Garcia-Pelegrin *et al.*[13] highlight the value of comparative studies of perception and cognition. Differences between species in limb anatomy and mode of life produce striking differences in how these animals perceive the world around them, which can be measured using clever experimental methods. This research also highlights the value of magic tricks as an experimental probe of perception and cognition[14]. Capuchin monkeys appear to experience magic tricks in much the same way that we do. This tells us something not only about these monkeys, but about ourselves.

DECLARATION OF INTERESTS

The author declares no competing interests.

REFERENCES

1. Torigoe, T. (1985). Comparison of object manipulation among 74 species of non-human primates. Primates *26*, 182–194. https://doi.org/10.1007/BF02382017.

2. Costello, M.B., and Fragaszy, D.M. (1988). Prehension in Cebus and Saimiri: I. Grip type and hand preference. Am. J. Primatol. *15*, 235–245. https://doi.org/10.1002/ajp.1350150306.

3. Ottoni, E.B., and Izar, P. (2008). Capuchin monkey tool use: Overview and implications. Evol. Anthropol. *17*, 171–178. https://doi.org/10.1002/evan.20185.

4. Westergaard, G.C., and Fragaszy, D.M. (1987). The manufacture and use of tools by capuchin monkeys (Cebus apella). J. Comp. Psychol. *101*, 159–168. https://doi.org/10.1037/0735-7036.101.2.159.

5. Napier, J.R. (1961). Prehensility and opposability in the hands of primates. Symp. Zool. Soc. Lond. *5*, 115–132.

6. Rilling, J.K., and Insel, T.R. (1999). The primate neocortex in comparative perspective using magnetic resonance imaging. J. Hum. Evol. *37*, 191–223. https://doi.org/10.1006/jhev.1999.0313.

7. Padberg, J., Franca, J.G., Cooke, D.F., Soares, J.G.M., Rosa, M.G.P., Fiorani, M., Gattass, R., and Krubitzer, L. (2007). Parallel evolution of cortical areas involved in skilled hand use. J. Neurosci. *27*, 10106–10115. https://doi.org/10.1523/JNEUROSCI.2632-07.2007.

8. Chaplin, T.A., Yu, H.-H., Soares, J.G.M., Gattass, R., and Rosa, M.G.P. (2013). A conserved pattern of differential expansion of cortical areas in simian primates. J. Neurosci. *33*, 15120–15125. https://doi.org/10.1523/JNEUROSCI.2909-13.2013.

9. Bortoff, G., and Strick, P. (1993). Corticospinal terminations in two new-world primates: further evidence that corticomotoneuronal connections provide part of the neural substrate for manual dexterity. J. Neurosci. *13*, 5105–5118. https://doi.org/10.1523/JNEUROSCI.13-12-05105.1993.

10. Dea, M., Hamadjida, A., Elgbeili, G., Quessy, S., and Dancause, N. (2016). Different patterns of cortical inputs to subregions of the primary motor cortex hand representation in Cebus apella. Cereb. Cortex *26*, 1747–1761. https://doi.org/10.1093/cercor/bhv324.

11. Sommerville, J.A., Woodward, A.L., and Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. Cognition *96*, B1–B11. https://doi.org/10.1016/j.cognition.2004.07.004.

12. Kuroshima, H., Kaiser, I., and Fragaszy, D.M. (2014). Does own experience affect perception of others' actions in capuchin monkeys (Cebus apella)? Anim. Cogn. *17*, 1269–1279. https://doi.org/10.1007/s10071-014-0760-1.

13. Garcia-Pelegrin, E., Miller, R., Wilkins, C., and Clayton, N.S. (2023). Manual action expectation and biomechanical ability in three species of New World monkey. Curr. Biol. *33*, 1803–1808.

14. Macknik, S.L., King, M., Randi, J., Robbins, A., Teller, Thompson, J., and Martinez-Conde, S. (2008). Attention and awareness in stage magic: Turning tricks into research. Nat. Rev. Neurosci. *9*, 871–879. https://doi.org/10.1038/nrn2473.

15. Kuhn, G., and Land, M.F. (2006). There's more to magic than meets the eye. Curr. Biol. *16*, R950–R951. https://doi.org/10.1016/j.cub.2006.10.012.

16. Garcia-Pelegrin, E., Schnell, A.K., Wilkins, C., and Clayton, N.S. (2021). Exploring the perceptual inabilities of Eurasian jays (Garrulus glandarius) using magic effects. Proc. Natl. Acad. Sci. USA *118*, e2026106118. https://doi.org/10.1073/pnas.2026106118.

17. Buckmaster, C.L., Hyde, S.A., Parker, K.J., and Lyons, D.M. (2015). Cup tool use by squirrel monkeys. Am. J. Primatol. *77*, 1323–1332. https://doi.org/10.1002/ajp.22486.

18. Fogassi, L., Ferrari, P.F., Gesierich, B., Rozzi, S., Chersi, F., and Rizzolatti, G. (2005). Parietal lobe: From action organization to intention understanding. Science *308*, 662–667. https://doi.org/10.1126/science.1106138.

19. Molenberghs, P., Cunnington, R., and Mattingley, J.B. (2012). Brain regions with mirror properties: A meta-analysis of 125 human fMRI studies. Neurosci. Biobehav. Rev. *36*, 341–349. https://doi.org/10.1016/j.neubiorev.2011.07.004.

20. Turella, L., Rumiati, R., and Lingnau, A. (2020). Hierarchical action encoding within the human brain. Cereb. Cortex *30*, 2924–2938. https://doi.org/10.1093/cercor/bhz284.