with the random movements of intracellular particle probes [11,12] to confirm that buckling occurs in pockets of weakened cytoskeleton.

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Naturalizing Cognition: The Integration of Cognitive Science and Biology

Descartes drove a wedge between human cognition and biology. Cognitive neuroscience is beginning to bridge the gap, and the application of mirror neuron theory to a range of problems in psychology has demonstrated the possibility of developing an understanding that spans from neural anatomy to language and empathy.

Arthur M. Glenberg

When Descartes reasoned from "cogito ergo sum" he allowed for progress in biology by divorcing it from church-controlled thinking about human psychology. Descartes' division was taken up by influential cognitive scientists who forged a psychology based on the computer metaphor: Thinking, it was proposed, is the manipulation of symbols by rules [1]. The symbols were stripped of all perceptual and motor content, thus becoming amodal, abstract and, importantly, implementable on computers. The claim became that, if a computer could be programmed to implement the correct algorithms, then the computer would not just be simulating thinking, it would be doing thinking. Although there have been strong objections to this claim [2], the elegant theorizing, the empirical successes and the apparent gap between body and mind forged a Cartesian program which has been generally adopted by the field of cognitive science. Recent findings [3,4], reported in this issue of *Current Biology*, which demonstrate the likely role of mirror neuron systems in language and social interaction, provide an alternative to Cartesian dualism and a natural science account of cognition.

The tremendous growth of cognitive neuroscience in the last two decades, fueled by the increasing availability of brain imaging technologies, began to bridge the gap between body and mind by demonstrating that coherent brain activity could be correlated with both simple and complex cognitive activity. But the proper explanation of those correlations remained elusive, in part because the images were interpreted in the context of Cartesian cognitive theories that did not reach down to the neural mechanisms. The discovery of mirror neurons helps to bridge the gap between cognition and biology by providing a neural mechanism that reaches up to psychological theory and suggests solutions to a range of problems in cognitive science [5,6].

Mirror neurons were first identified in area F5 of the macaque pre-motor cortex by single-cell recording. These neurons fire both when the animal engages in particular actions, such as grasping a peanut, and when the animal observes the experimenter grasp the peanut in a similar manner. Many of these neurons are specific to the type of grasp, such as a precision grip or a power grip, as well as the intent of the grip, for example, to place or to eat. Furthermore, the same neuron may also respond to the sound of the action, such as the sound of breaking open a peanut. Additional research has identified mirror neurons in the inferior parietal lobule [7].

The existence of mirror neurons strongly suggests a motor resonance mechanism for action recognition and understanding. That is, using the mirror neuron mechanism, animal A understands animal B's action and intent as the same action and intent that it would have in this situation [7]. Recognizing the intent of conspecifics would seem to be a prerequisite for sophisticated social organization, allowing learning from imitation and

facilitating communication. Thus, mirror neurons might serve as a substrate for many of the functions cognitive scientists deem important. Furthermore, interest in human mirror neurons is heightened by the fact that macaque area F5 is the likely homolog of the human Broca's region, which has long been associated with control of speech [5].

In humans, mirror neurons have been studied predominately by using imaging techniques, although transcranial magnetic stimulation and other methodologies have also been used. The justification for concluding that imaging data represent a mirror neuron system comes from satisfying three criteria. First, signal modulation, for example in the BOLD signal of functional magnetic resonance imaging (fMRI), has been detected in regions homologous to those known to contain mirror neurons in the macaque, such as Broca's region, pre-motor cortex and anterior intraparietal sulcus. Second, activity in these areas is modulated by motor activity, for example, the participant grasping. Third, activity in the same areas is modulated by observation of similar actions in others; that is, if area A is differentially responsive to literal grasping and area B is differentially responsive to literal mouth movements, then area A is differentially responsive to observed grasping and area B differentially responsive to observed mouth movements.

The research reported by Aziz-Zadeh *et al.* [3] makes a strong case for the use of a mirror neuron system during language comprehension. While being scanned, participants read phrases describing mouth, hand or foot actions. In a later session, the same participants observed videos of the same actions. Analyses demonstrated left-lateralized activations with specific areas for mouth, hand and foot actions . That in itself is quite remarkable: remember that differential activation is observed in motor and pre-motor areas, but the stimuli were visual and linguistic. The other remarkable finding is the overlap of activation (observed on a subject by subject basis) produced by linguistic and visual stimuli. That is, reading the phrase "bite the peach" generates activation in the same motor areas as observing someone biting a peach.

Why should this overlap occur? Recent work in linguistics [8], philosophy [9], and psychology [10] has supported the claim that meanings of both situations and sentences are grounded in, that is, depend upon, bodily activity of perception, emotion and action. For example, Glenberg and Kaschak [11] used behavioral techniques to demonstrate that understanding sentences describing the transfer of both concrete objects, such as a pen, and abstract information, such as an idea, calls upon motor systems. The new work of Aziz-Zadeh *et al.* [3] is consistent with this sort of behavioral research and relates the findings to mirror neurons, thereby helping to produce a reduction of psychological theory and phenomena to the neural level.

Gazzola *et al.* [4] are among the first to investigate an auditory mirror neuron system in humans. In the first day of the experiment, participants listened to easily identified sounds produced by the mouth, as in kissing, or hand, as when ripping paper. In the second day, the participants manipulated unobserved objects with the mouth or hand. Much like Aziz-Zadeh *et al.* [3], Gazzola *et al.* [4] found that left-lateralized activity in ventral pre-motor areas overlapped for mouth actions and mouth sounds, and that activity in more ventral pre-motor areas overlapped for hand actions and hand sounds. Because data were available from these participants during visual observation of hand actions, they were also able to demonstrate that some of the hand auditory mirror neuron areas also responded to the visual observation of similar hand actions. Thus, people may rather directly understand the meaning of sounds as the actions that they themselves produce that result in those sounds.

As noted above, part of the appeal of the mirror neuron construct is the possibility that it helps to explain social and clinical phenomena [6]. Along these lines, Gazzola *et al.* [4] report an amazing correlation: people with greater activation of auditory mirror neuron areas show a corresponding higher level of empathy, as measured by a paper and pencil measure of perspective taking. Such findings encourage the investigation of the relation between mirror neuron systems and clinical phenomena such as autism [12].

Although these data are consistent across human fMRI studies (and across species), several precautions need to be considered. First, although both sets of investigators took steps to reduce the possibility that the results are due to strategic (conscious) effects such as imagining the actions after hearing a sound, the procedures do not as yet completely rule out this alternative. Second, fMRI results are inherently correlational and cannot be used to demonstrate with certainty a causal relation between activity in a particular brain region and a psychological phenomenon. Third, even if the mirror neuron explanation is correct, many important questions remain such as how (or if) mirror properties are learned, the degree of inter-species and inter-individual variation, and how mirror systems might be related to more abstract language and thought [13].

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Convergent Evolution: Gene Sharing by Eukaryotic Plant Pathogens

Oomycetes and filamentous parasitic fungi are plant pathogens that have undergone convergent evolution. A recent study has shown that these microbial eukaryotes have exchanged metabolic genes, which might explain some of their phenotypic similarities.

Jan O. Andersson

There are many examples in nature of the independent evolution of similar phenotypic traits in phylogenetically unrelated lineages — a well known one being the wings of birds, bats and bees, the common ancestor of which was unable to fly. Convergent evolution also occurs in microbial organisms. Different bacterial and eukaryotic human parasites, for example, have independently adapted to a life inside a human host [1].

For prokaryotes, the co-occurrence of unrelated organisms in the same physical environment can lead to sharing of genes via an evolutionary process known as lateral gene transfer [2] (Figure 1). This gene exchange could be both the cause and consequence of adaptation to similar environments, and result in extensive convergent evolution [3]. In this issue of *Current Biology*, Richards *et al.* [4] report evidence that gene sharing also occurs between microbial eukaryotes and argue that this might explain apparent convergent evolution between eukaryotic plant pathogens (Figure 1).

The economically most important eukaryotic plant pathogens are found among the oomycetes and the fungi — for example, the Irish potato famine was caused by the oomycete *Phytophthora infestans*, and the rice blast disease is caused by the filamentous fungus *Magnaporthe grisea*. Interestingly, because of their fungus-like appearance, oomycetes were previously considered to belong to the fungi, but evolutionary studies now place them within Stramenopiles, as a sister group to diatoms, one of the dominant phytoplankton in the ocean, while fungi form a sister group to animals [5].

Despite this reclassification, oomycetes obviously share a number of phenotypic traits with pathogenic fungi, such as filamentous growth in the vegetative stage, the ability to form spores for both sexual and asexual reproduction, and similar modes of colonization of host plants. For example, oomycetes produce plant cell-wall degrading enzymes that are very similar to their fungal counterparts [6]. Thus, filamentous pathogenic fungi and oomycetes are an excellent example of convergent evolution among microbial eukaryotes. Richards *et al.* [4] set out to see if they could identify footprints of this convergence left in the genomes of the two groups.

Richards *et al.* [4] used the genes identified in the genome project of the parasitic fungus *M. grisea* [7] in similarity searches against twenty other genomes, representing the diversity in the tree of life, including mostly eukaryotic species with several fungi and the oomycete *Phytophthora ramorum* represented. If the similarity score was higher to the oomycete plant pathogen sequence than to any of the included fungal sequences, they treated the gene as a candidate for having undergone lateral gene transfer. Phylogenetic analyses were then performed for eleven such cases.

Interestingly, eight oomycete genes encoding enzymes with putative functions related to the utilization of rare metabolites were found to be associated with fungi in the phylogenetic analyses [4]. In four cases, the oomycete genes were nested, with strong statistical support, within the group as a sister clade to filamentous pathogenic fungi, strongly indicating that in the evolutionary past the genes had undergone transfer from fungi to oomyces. The acquisition of these genes by oomycetes likely provided a metabolic advantage which helped them to adapt to an osmotrophic lifestyle which might have facilitated a lifestyle allowing colonization of plants; the evolution of pathogenicity is usually coupled with changes in the gene inventory [1]. In any case, these examples clearly illustrate that genetic material can move between different eukaryotic kingdoms [4], which is a remarkable finding. But was it really unexpected?

There is a common misconception that eukaryotes are immune to lateral gene transfer. Although the initial claims of transfer of more than a hundred genes from bacterial lineages to