Expanding the mirror: vicarious activity for actions, emotions, and sensations

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We often empathically share the states of others. The discovery of 'mirror neurons' suggested a neural mechanism for monkeys to share the actions of others. Here we expand this view by showing that mirror neurons for actions not only exist in the premotor cortex or in monkeys and that vicarious activity can also be measured for the emotions and sensations of others. Although we still need to empirically explore the function and development of these vicarious activations, we should stop thinking of vicarious brain activity as a peculiar property of the premotor cortex: instead it seems to be a very common phenomenon which leads social stimuli to recruit a wide range of seemingly private neural systems.

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Introduction

Whenever we see what happens to others, we not only *understand* what they experience but also often empathically *share* their states. In the nineties a series of experiments carried out in Parma evidenced that some premotor neurons, called mirror neurons, fired not only during action execution, as a premotor neuron 'should', but also during the observation of the same action [1]. These vicarious motor responses inspired an understanding of the neural basis of empathy; we might empathically share the states of others because seeing their states triggers representations of corresponding states in our brain. The aim of this review is to highlight two developments of the last years. First, mirror neurons responding during the execution and perception of actions not only exist in the premotor cortex or in monkeys, but also other brain regions and species have similar properties.

Second, we also recruit brain regions responsible for our own sensations and emotions while we perceive those of others, and these various systems are intimately interconnected. While we still need to empirically explore which of the many possible functions these shared systems really serve in the brain, and how they develop, these new findings encourage us to see mirror neurons in the premotor cortex as the best understood example of a wider class of vicarious neural responses encompassing the domains of actions, sensations, and emotions.

Mirror neurons for actions outside the premotor cortex

The presence of mirror neurons in the ventral premotor cortex of macaques has now been confirmed by multiple research groups [2,3] and mirror neurons also respond to the sound of actions [4,5], and represent actions at different levels of description (Box 1). Similar neurons responding during the observation and execution of hand actions also exist in the anterior sectors of the inferior parietal lobule [3,6•] (Figure 1b). While many still consider mirror neurons to be restricted to ventral premotor and inferior parietal cortex, if all neurons that respond during the execution and perception of a particular action are called 'mirror neurons', there is mounting evidence that such neurons exist elsewhere. Some neurons in a different sector of the posterior parietal cortex (area LIP) demonstrate increases in firing rate both when the monkey programs an eye movement toward particular locations in space and when seeing another monkey look toward that location [7••]. Some neurons in the dorsal premotor cortex are active both when a monkey moves a cursor on the screen and when it sees the cursor being moved to the same target by another individual [8]. These dorsal premotor neurons raise an interesting question: should the term 'mirror' be reserved to neurons that require seeing the other individual perform an action, or is it enough if the neuron is triggered by seeing the *consequences* of the actions (i.e. the movement of the cursor caused by the action). We favor the latter because the effect on the organism is similar: recruiting motor programs while witnessing the actions of others, be it through the perception of the action or its consequences. Overall, these new findings show that mirror neurons had only been described in the ventral premotor and anterior inferior parietal cortex not because they only exist in these areas, but because these areas were the ones systematically explored for the presence of mirror neurons. Most of the brain still remains a *terra incognita* when it comes to mirror neurons (question marks in Figure 1b).

Mirror properties in humans and birds

The last years have seen a number of exciting methodological advances to establish the presence and study the localization of the mirror neuron system in humans. One of the most elegant demonstrations of the presence of mirror neurons in the human ventral premotor cortex stems from transcranial magnetic stimulation (TMS): viewing an action increases motor evoked potentials in the same muscle, evidencing that the vision of an action triggers neurons involved in the execution of that action; most importantly, this effect disappears after transient inactivation of ventral premotor cortex, showing that the integration of perception and action occurs at least in part in the same brain region as in the monkey [9••].

fMRI repetition suppression is based on the assumption that if two tasks A and B depend on the same neurons, performing A before B will reduce the response to B. It has now been shown that, in addition to the ventral premotor cortex, the dorsal premotor cortex and inferior parietal lobe also show reduced activity to the execution of an action that follows the observation of the same action [10,11] and vice versa [11,12•], demonstrating that in these regions, the observation and execution of an action recruits the same neurons, that is they contain mirror neurons.

Single cell recordings in the human SMA and temporal lobe [13•] finally demonstrate that single neurons in these brain regions also respond to both the observation and execution of the same action.

In conclusion, there is now hard evidence that at least five brain regions of the human cortex contain mirror neurons: the ventral and dorsal premotor cortex, the supplementary motor cortex, the inferior parietal lobe, and the temporal lobe.

Analyzing single participant during action observation and execution without smoothing the data has demonstrated that voxels with mirror properties (i.e. active during action observation and execution) exist in each participant and are located in the abovementioned regions as well as in the somatosensory cortices (see below) and cerebellum [14•] (Figure 1c). However, whether these two additional candidate areas truly contain mirror neurons remains to be tested, and we suggest using the term putative Mirror Neuron System (pMNS) when including these candidate areas into the mirror neuron system.

Mirror neurons also exist in songbirds, in which neurons of the telecephalic nucleus HVC respond both when the bird itself sings and when it hears other birds sing [15••] (Figure 1a) and similar neurons also exist in the bird's auditory association region, Field L [16].

Figure 1
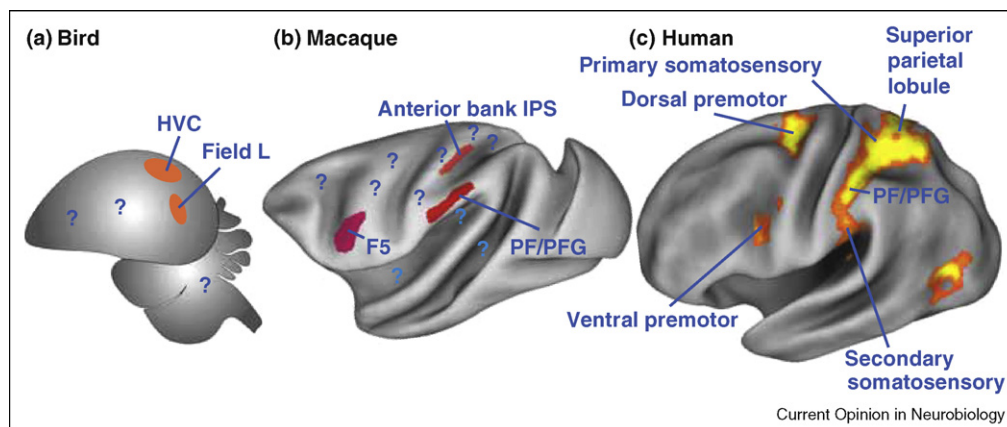
Location of mirror neurons in birds **(a)**, macaques **(b)** and of voxels showing mirror properties in humans **(c)**. Many regions have not been explored yet for the presence of mirror neurons in animals, and this is symbolized by the presence of question marks in various locations.

Box 2 How do we get to have mirror neurons?

Mirror neurons could be inborn. The presence of neonatal imitation of certain facial expressions, tongue protrusion in particular, in human [49] and monkeys [50] suggests we have mirror neurons for certain motor programs at birth. Considering the enormous flexibility in the motor repertoire of primates, it is unlikely however that all mirror neurons are genetically preprogrammed. It has been proposed that some mirror neurons may be the result of Hebbian association learning between the motor programs that generate a novel action and the sensory reafference, that is what this novel action looks and sounds like [51–53]. Two experiments support this plasticity. First, three hours of piano lessons to musically naïve participants is enough to cause the premotor cortex to start responding to the sound of piano playing [54•], suggesting that mirror neurons for a new action (piano playing) can be formed within a few hours of sensory-motor contingency. Second, training people to respond to the sight of an action by performing a different action can influence the way the motor system is reacting to seeing that behavior [55]. The idea of Hebbian association could also help explain the emergence of vicarious somatosensory responses: each time we see an object touch our skin, we feel a tactile sensation on our skin. This contingency could reinforce synapses between visual and somatosensory neurons and cause somatosensory neurons to start fire to the vision of an object approaching the corresponding bodypart of either the individual himself or others [24••]. One of the challenges for such a Hebbian account is that we seem to have vicarious motor and somatosensory activations even for bodyparts we do not typically see (e.g. facial expressions) [52].

This wide spread of mirror neurons in the brain and across species begs us to reconsider what mirror neurons are. Instead of defining them as *premotor* neurons that respond to the observation and execution of the same action we propose to extend the definition to any neuron involved in the execution of a motor action that shows significant vicarious activity to the observation of corresponding actions performed by others. Such a definition would encompass mirror neurons in other species such as birds that do not have a premotor cortex and neurons with mirror properties in motor brain regions outside of the premotor cortex. This extension also raises the question of how so many regions come to have mirror neurons (see Box 2) and whether vicarious responses are a more general phenomenon that can also be measured in brain regions involved in other functions such as somatosensation and emotions.

Vicarious somatosensory activity

In humans somatosensation is organized along multiple parallel processing streams. SI in the anterior parietal lobe is composed of four different cytoarchitectonic regions, Broadman areas (BA) 3a and 3b in the posterior bank of the central sulcus, BA1 on the crown of the postcentral gyrus, and BA2 in the anterior bank of the postcentral sulcus. Of these subregions, only those in the central sulcus receive their primary input from the thalamus and should be considered SI proper. For passive tactile stimuli, such as an object touching your leg, information travels from the thalamus to BA3b, then to BA1, and then to SII in the parietal operculum. For active tactile stimuli,

such as searching for your keys in your pocket, proprioceptive information is additionally sent to BA3a and onwards to BA2 where this proprioceptive information integrates with tactile information from BA1. This highly integrated information is then sent to SII and the posterior parietal lobe. Importantly, unlike BA3a and 3b, BA2 and SII receive direct input from regions of the posterior parietal lobe that are known to have visual responses, including regions PF/PFG and VIP. Region BA1 only receives very weak direct input from these regions. On the basis of this connectivity pattern, one might speculate that BA2 and SII could show the strongest, BA1 weaker, and BA3a, 3b the smallest visual, and therefore vicarious, activity. Functional neuroimaging data seem to confirm this prediction for both the observation of passive and active touch.

The observation of other people's hands [17], legs [18], neck, or face [19] being touched indeed triggers activity in regions of SII also responding when participants are touched on the same body part. In the same experiments, BA3a, 3b, and BA1 are not reliably vicariously activated although they show robust responses when the participants themselves are being touched, making them 'private', that is reserved to the experience of our own tactile experiences. This distinction between early and late somatosensory processing stages finds further support from an elegant study that exploits the exquisite temporal resolution of EEG: the first 40 ms of the somatosensory evoked potential, corresponding to activity up to and including BA3 are not modulated by the concurrent view of another individual being touched, while the latter components, corresponding to activity in BA1 and SII, are [20]. In agreement with the anatomical data, visual information from posterior parietal brain regions, therefore, seems to trigger vicarious tactile representations along a top-down gradient, with such activity being strongest in SII, weaker in BA1, and absent in BA3a and 3b.

Also hearing or seeing others manipulate objects during goal directed behavior seems to consistently activate the higher level of somatosensory processing, in particular BA2 and also SII [14,21]. Earlier stages of processing in SI seem spared from such vicarious activity during action observation. Importantly, the pattern of activity in BA2 during action perception conveying significant information about what actions another individual is performing [22•] and also in the monkey, glucose uptake is augmented in the hand representation of SI while observing the hand actions of other individuals [23]. Considering how central somatosensation is to normal motor control, one might therefore speculate that vicarious BA2 activity might play a similarly important role in the perception of certain, somatosensory aspects of other people's actions, thereby complementing the well established role of classical mirror neurons in premotor and posterior parietal

regions. On the basis of the role of BA2 during haptic exploration, BA2 might be particularly important for inferring the properties of objects from the way we see other people manipulate them (e.g. how heavy is that object?). Examining the impact of virtual lesions to BA2 while participants try to judge such properties will be key to test this prediction.

Single cell recordings in monkeys further show that posterior parietal regions that are anatomically connected with SII and BA2 indeed have the visual properties it would take to trigger vicarious responses in the somatosensory cortices: neurons in area VIP and PFG respond both to the experience of touch on the monkey's face and forelimb, respectively, and to the vision of objects close to or touching the face and forearms, respectively, of an experimenter sitting in front of the monkey [24[••]]. This important study therefore not only provides the first single cell evidence that the vision of other people getting touched indeed triggers neurons involved in the experience of touch on the same body part in the self, but also shows that the same brain regions that are thought to provide the premotor mirror neuron with visual information could also provide BA2 and SII with the information required for triggering vicarious responses in the somatosensory cortex.

Indirect evidence for a role of vicarious tactile activity in social perception also comes from the study of people that show unusually high vicarious somatosensory activity. Approximately 1% of humans report literally feeling on their own skin what they see happen to others — to the point where they become impaired in reporting where they have been touched on their own body when they simultaneously see other people being touched elsewhere [25]. One of these mirror-touch synaesthetes has been scanned while viewing touch, and a hyperactivation of her BA2 and SII was measured compared to controls [19]. Interestingly, mirror-touch synaesthetes also rank exceptionally high on empathy questionnaires [25], suggesting that the more you vicariously recruit BA2 and SII, the more vividly you experience the tactile sensations of others and the more you are inclined to empathize with others in general.

Although activations in somatosensory cortices during the observation of actions and touch are reminiscent of mirror neurons, the former involve regions that process sensory *input* while the latter recruit regions involved in programming motor *output*. It is therefore important to distinguish these two phenomena as different examples of vicarious activation that could rely on different neural circuits.

Vicarious emotional activity
Emotional brain regions also seem to be vicariously activated while participants perceive the emotional states of others. Viewing facial expressions that convey emotions, be it disgust [26,27], happiness [26,28], pain [29,30], or a combination of different emotions [31], activates regions of the anterior Insula and adjacent Frontal Operculum (jointly referred to as I/FO) involved in experiencing similar emotions as triggered by olfactory [27], gustatory [26] or nociceptive [29] stimuli. Seeing the body parts of others being injured, witnessing arbitrary cues signaling the pain of others or even reading about the emotions of others all trigger the I/FO vicariously [32]. Together these findings suggest, that representations of emotional bodily states in the I/FO can be triggered by many sources of information signaling that another individual is experiencing similar emotional states.

We unfortunately still lack systematic single cell recordings from the I/FO to establish whether single neurons, responding during the experience of an emotion, are also triggered by the perception of that emotion in others. However, neurological studies show that lesions in the I/FO impair both the experience of certain emotions and the recognition of similar emotions in others [33–35] supporting the role of the I/FO in social perception.

While we can directly perceive the actions of others, we have to deduce their emotions from their actions (e.g. facial expressions), visible bodily causes (e.g. a syringe penetrating a hand is likely to trigger pain), or more arbitrary cues such as language (e.g. 'I'm very sad today'). Anatomically, the I/FO receives input from the prefrontal cortex, the motor system and all sensory modalities. Functional connectivity analyses now increasingly disentangle which of these sources of input trigger vicarious activity in the I/FO in specific cases: Broca's area, the temporal pole, and the SMA, while reading about emotions [36], the premotor regions involved in producing similar facial expressions while viewing facial expressions [28,31,37] and the superior temporal sulcus while deducing pain from viewing bodily causes [38]. Together, these data suggest that the I/FO may flexibly interact with a broad range of brain areas, including those involved in motor simulation, to trigger representations of emotions that match those of the people around us.

Vicarious activations and cognition
In contrast to early works that contrast embodied and cognitive views of social cognition, researchers increasingly embrace the fact that vicarious activations in the motor, somatosensory, and emotional system interact and sometimes depend on other, more cognitive brain systems involved in attention, mentalizing, and cognitive control: firstly, directing attention toward or away from actions modulates activity in pMNS regions [39]. Secondly, asking participants to reflect about the *intentions* behind observed actions triggers activity in mentalizing, in addition to motor, brain regions [40,41], suggesting that motor simulation could provide an input to 'mentalizing' brain regions [42]. Thirdly, if people are asked to switch

from doing the same to doing the opposite of another individual to achieve a common goal, cognitive control brain regions activate alongside mirror regions [43•]. These regions are probably necessary to determine, based on current goals, whether mirror representations of the observed actions will be executed or whether representations of complementary actions get to be executed. In addition, empathizing with the emotions of others can be modulated by prior knowledge about the fairness of the victim, cognitive appraisal, and perspective taking (see [44] for a review).

Conclusions

In summary, the last years have seen an explosion of evidence to suggest that vicarious activations are not restricted to monkeys, actions, or the premotor cortex: firstly, humans and birds have mirror neurons; secondly, many other brain regions involved in motor execution seem to be vicariously activated during the observation of other people's actions; thirdly, in addition to motor representations, our brain also seems to vicariously trigger somatosensory and emotional representations while viewing others being touched, perform actions, or experience emotions. Instead of a vision in which the ventral premotor cortex is a singular brain region endowed with a unique mirror property that would single-handedly shed light onto the inner lives of others, these findings draw a less monochromatic picture: vicarious activity can be measured in many brain regions — including motor, somatosensory, and emotional cortices. The flexible interplay of these circuits with brain regions associated with attention, cognitive control and mentalizing may be what allows us to feel and empathize with the inner lives of others. In support of this idea, lesions in somatosensory, insular and premotor regions all seem to impair our capacity to feel the emotions of others [33–35]. Understanding the precise function of each of the many vicariously recruitable brain regions in social perception however remains an important challenge for future research.

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