Imitation

Aude G. Billard

Introduction

Imitation—the ability to recognize and reproduce others' actions—is a powerful means of learning and developing new skills. Species endowed with this capability are provided with fundamental abilities for social learning. In its most complex form, imitation provides fundamental capabilities for social cognition, such as the recognition of conspecifics, the attribution of others' intentions, and the ability to deceive and to manipulate others' states of mind. Improved understanding of animals' ability to imitate can contribute to both biological and engineering sciences.

Research on imitation builds a bridge between biology and engineering, and between the study and use of imitation. Biology seeks to better understand the cognitive and neural processes behind the different forms of animal imitation, and how these relate to the evolution of social cognition. Engineering uses studies of the biological processes of human imitation to design robot controllers and computational algorithms enabling learning and imitative skills similar in robustness and flexibility to human skills.

There are three major levels of modeling. *Theoretical modeling* derives models of the cognitive mechanisms behind imitation based on behavioral studies of humans' and other animals' imitation. *Computational modeling* builds models of the neural mechanisms, and their brain correlates, behind imitation learning in human and other animals. *Robotics modeling* designs algorithms for imitation learning, implementable in hardware systems, that allow a robot to be taught by demonstration.

Theoretical Modeling

The study of imitation encompasses a large range of disciplines, including ethology, neuroscience, psychology, and linguistics.

For ethologists, the major issue is to define what behaviors the term *imitation* refers to and in which species these behaviors are exhibited (for reviews, see Whiten, 2000; Heyes, 2001). Animal imitation seems best described in terms of levels of complexity. Imitation (or "true" imitation) is contrasted to mimicry or copying. True imitation is the ability to replicate and, by so doing, learn skills that are not part of the animal's prior repertoire, by observation of those performed by others. Mimicry, in contrast, is the ability to replicate a behavior that is usually part of the usual animal repertoire. We can also distinguish imitation forms that do or do not require the ability to interpret intentions, and, more generally, a theory of mind. The current view favors the idea that theory of mind is not necessary for most low-level forms of imitation (such as copying or mimicry).

Simple forms of imitation that probably require no understanding of intention or theory of mind are found in, e.g., rats and monkeys (Heyes, 1999). AQ=1 These species' copying ability is generally considered to be an instance of *social facilitation*, in which the correct behavior is prompted by the social context. This simple imitative behavior seems to rely on a form of associative learning that accepts temporal delays, imprecise timing, and incomplete cues. Observation might enhance learning by restricting the associations to only the sensorimotor pathways that are activated during observation. For example, in rats, pushing the correct lever is associated with odors, not colors, when colors are an invariant across the observed trials.

More complex forms of imitation are demonstrated by apes and dolphins. Chimpanzees and orangutans can master simple sequential, manipulatory tasks. They are capable of replicating part of the observed behavior in a different context than that in which it was observed. Dolphins can be trained to copy long sequences of body movements following human demonstration, showing an ability to map different body structures to their own (they respond to the demonstrator's movements of the legs and arms with similar movements of their tail, and fins respectively).

These more complex forms of imitation are set apart from simpler ones because they encompass the ability to reproduce *sequences* of actions and the ability to *transform* the actions so as to produce variations (subparts) of the observed behavior in the same or a different context (see, e.g., Byrne and Russon, 1998; Heyes in Dautenhahn and Nehaniv, 2002).

The ability to imitate reaches its fullest complexity in humans. Humans can imitate any actions of the body based on a variety of purposes or goals, such as the goal of reproducing the aesthetic (e.g., dance), efficiency (e.g., sport), or precision (e.g., surgery) aspect of the movement. Imitation in humans extends to verbal and facial expression, and from there to high-level cognitive and behavioral skills. It is a fundamental means to relate socially to others, and people who are impaired in their imitative skills, such as people with autism, also show general impairment in other social skills. For psychologists, imitation is crucial to the child's growing capacity for representation and symbolization.

Imitation can be *immediate* or *deferred*, depending on whether the replication occurs within a short (few minutes) or long (hours, days) time after the demonstration. It may be partial or selective (when only part of the imitative behavior is replicated), goal-directed (when only the means–end of the demonstration is perfectly reproduced), or exact (Bekkering and Prinz in Dautenhahn and Nehaniv, 2002).

Meltzoff and colleagues' work contributed to redefining the developmental stages of children's imitation proposed by Piaget in *Play, Dreams and Imitation* (see Meltzoff and Moore, 1999). In infants, immediate imitation of facial expression appears soon after birth, suggesting an "innate" kinesthetic-visual mapping.* Deferred imitation appears as early as 9 months, implying a growing capacity for internal representation of others' movements. Generalized imitation involving numerous modalities, such as vocal and verbal imitation and the ability to imitate a great variety of actions, begins around 15 to 18 months.

An important body of research in linguistics studies vocal and verbal imitation in birds, with the goal of understanding the role that hearing plays in tuning speech production and how this can relate to similar developmental processes in human infants (see Doupe and Kuhl, 1999). Young birds' songs mature in the presence of a tutor (usually the parent bird) and are species and region specific. Parrots and mynah birds are particularly intriguing because of their ability to reproduce segments of human speech. The study of birds' neural structures for vocal imitation may allow parallels to be drawn to similar neural structures in humans.

Taken together, the evidence from psychology and ethology shows that imitation results not from a single mechanism but from several cognitive mechanisms that are multimodal (audiomotor, visuokinesthetic-motor) in essence and are used for other (nonimitative) behaviors. Visuomotor imitation is better understood at this stage than is vocal imitation, as it can profit from the large body of literature on perception and production of motion. Findings from these studies directly relevant to the study of imitation are briefly summarized next.

Motion Perception

Since Johansson's landmark study in 1973, an abundance of literature has demonstrated the capacity of humans to recognize biological (especially human) motions from a limited number of cues (these studies use point-light display techniques that allow the viewer to see only one point for each moving limb) (for a review, see Dittrich, 1999). Humans can easily make out the general features of the motion, distinguishing the type of gait or the type of action, as well as specific features, such as the weight of an object being lifted or the age and sex of the walker. More important, humans are quite capable of distinguishing between biological and nonbiological motions. This ability relies on powerful visual mechanisms for quickly extracting relevant features from the kinematics of multiple-joint motion. Some of these features are the phase or relationship across limb motion, the orientation, and the speed of limb movement.

Motor Control

Although there is evidence that the brain can recognize motion from a limited number of clues, it is not yet understood which information is used to recognize and to reproduce the motion. Because of the redundancy of multiple-joint motion, the information offered in point-light display experiments is usually not sufficient to lead to a single plausible solution. It seems, therefore, that the mechanisms humans use to assist in visual reconstruction of motion rely on models of the structure of the human body and the dynamics of its possible motion.

Evidence that the central nervous system (CNS) uses models of body dynamics to direct motion also comes from purely motor control studies (see Motor Control). The idea is that, rather than relying on sensory feedback (which is too slow to reach the CNS in time for the next motor command), the CNS uses *feedforward control* to control movements; that is, it uses *inverse forward* models to predict the expected outcome of a command as well as to estimate the current position and velocity of the moving limbs.

In summary, evidence from psychophysical studies of motion perception and from motion studies suggest that, to achieve a good replication of movements from a paucity of visual cues, the brain uses models of human kinematics and dynamics of motion. Moreover, it is likely that visual and motor representation of movements bear a close relationship for the mapping to be immediate and precise. It is not yet understood how the CNS builds these representations.

Computational Modeling

The challenge faced by computational modeling is to construct a model that can account for all the instances of imitation reported in the literature. The model should provide a means of naming and distinguishing animal imitative abilities, following a list of fundamental cognitive components. This hierarchical representation of animal imitation should follow the evolutionary tree, such that the different cognitive processes can be linked to the evolution of specific neural structures. We review next the evidence for neural structures specific to imitation.

Neural Structures Behind Visuomotor Imitation

Imitation has been a topic of research primarily in the cognitive and psychological sciences; Only recently has imitation become the explicit topic of a number of neuroscience studies. This new trend started with the discovery of the *mirror neuron* system (Rizzolatti et al., 1996), a neural circuit in F5 area of monkey premotor cortex that is active both when the monkey observes another monkey or a human grasping or manipulating objects and when the monkey performs the same manipulation. The mirror neuron system has been proposed as the link between visual and motor representation that is necessary to learn from the observation and imitation of others' actions. Evidence from brain imaging studies (e.g., Decety et al., 2002) suggests the existence of a similar system in humans involving predominantly Brodmann's areas 44 and 45 (Broca's areas), 40 (parietal lobe), and 21 (superior temporal sulcus).

Evidence that specific areas of the human brain contribute to imitation also comes indirectly from lesion studies. Studies of abnormal imitative behavior can be separated in two groups:

1. Patients suffering from a lack of or strong deficiency in the ability to imitate. Patients with ideomotor apraxia after parietal lesion are unable to make symbolic gestures or to act out the use of an object in response to an oral request (DeRenzi, Motti, and Nichelli, 1980). It is unclear whether ideomotor apraxia results from a deficit in motor imagery mechanisms or in motor execution. Apraxic patients are sometimes also incapable of recognizing a correctly produced gesture when given a stationary (photograph) or moving visual presentation. This suggests that the parietal lobe provides the locus of a neural network responsible for the translation of mental representation into movement production. However, the absence of systematic co-occurrence of ideomotor apraxia and

impairment in gesture recognition indicates that motor imagery and motor execution remain two separate processes, even if closely interconnected.

2. Patients displaying obstinate imitation behavior, that is, a compulsive imitation behavior that cannot be stopped easily by command. Patients with frontal lobe damage sometimes display imitation behavior in which they imitate the examiner's gestures without being so instructed (Lhermitte, Pillon, and Serdaru, 1986). This type of disorder supports the view that the frontal lobe modulates (mainly inhibits) a subcircuit that continually interprets visual observation of movements through the activation of motor patterns that would produce the same movements (a typical mirror neuron circuit).

Taken together, evidence from lesion studies and brain imaging suggests a major role for parietomotor connectivity as a basic circuit (possibly the mirror neuron system) behind movement imitation, and it also highlights the importance of frontoparietal connectivity in regulating this circuit.

Since its discovery, the mirror neuron system has led to a number of speculations about its role in imitation. However, evidence to support these hypotheses is still lacking. Research on the human mirror system is still in its early stages. So far, studies (corroborated by different laboratories) have addressed only simple actions of the arms and hands (fingers). It remains to be shown that mirror neurons exist for driving motion of other limbs, and to understand their role in driving imitation and imitation learning of complex actions (so as to qualify as "true imitation").

Computational modeling investigates some of the possible implications of a high-level representation of movements common to both visual and motor systems (a mirror neuron system) for imitation learning. In this quest, Oztop and Arbib developed a computational model of monkey mirror neuron system (see Arbib et al., 2002, and LANGUAGE EVOLUTION: THE MIRROR SYSTEM HYPOTHESIS). The model accounts for the role of the parietal lobe and F5 area in recognition and control of grasping. In particular, it gives a description of how, through learning of performing grasps, visuomotor (from parietal lobe to F5) connectivity can be built.

At a higher level of abstraction, computational models of the neural and cognitive correlates to human imitation are developed. Demiris and Hayes's model (in Dautenhahn and Nehaniv, 2002) gives an account of the cognitive processes behind imitation, in which the motor system is either active (active imitation) or passive (passive imitation) during perception. The active imitation mode encompasses a motor imagery mechanism (a type of mirror system) in which the same motor structures used in producing motion are used during visual perception for classification and recognition of motion.

Billard's (1999) model gives a high-level, comprehensive, but simplified representation of the visuomotor pathway behind learning by imitation, from processing real video data to directing a dynamic simulation of a humanoid or an actual robot (Figure 1). The model has composite modules whose functionalities were inspired by those of specific brain regions, incorporating abstract models of the superior temporal sulcus (STS), the spinal cord, the primary motor cortex (M1), the dorsal premotor area (PMd), and the cerebellum. Each part is implemented at a connectionist level, where the neuron unit is modeled as a *leaky integrator*. Neurons in the PMd module respond both to visual information (from STS) and to corresponding motor commands produced by the cerebellum. The STS-PMd-M1 interconnection is a simplified model of a mirror neuron system. The biological plausibility of the model was validated against kinematic recording of human motion (Billard, 1999) and functional magnetic resonance imaging (fMRI) data of human imitation of finger motion (Arbib et al., 2002).

Robotics Modeling

Robotics investigates the potential of imitation learning as a user-friendly means of human-robot interaction. The goal is to provide robots with the capacity for being reprogrammed in a non explicit fashion, that is, through demonstration. The challenge is to determine learning algorithms that are flexible across tasks and across platforms (robots).

An important issue dealt with by computational and robotic modeling is that of determining a measure of the similarity across demonstrator and imitator motions (Schaal, 1999; Dautenhahn and Nehaniv, 2002). For instance, when imitating grasping an object, one can reproduce one, a few, or all characteristics of the movements, and one can in principle reproduce (1) the goal of the movement (grasping the object with any effector following any path), (2) the goal of the movement and the correct effector (grasping the object with the correct hand), and (3) the detail of each joint movement, the motion of subsegments, and even the overall speed of movement. In each case, a different measure of the similarity between demonstrator and imitator movements must be used to account for the correctness of the reproduction. The measure should, in some cases, be qualitative, comparing the relationships across objects (which hand, which object), whereas in other cases it is quantitative, comparing the paths followed by each hand or comparing the angular trajectories of each joint.

In construction detailed imitations of joint motion, the problem is how to transfer human motions into robot motions, insofar as humans and robots have very different dynamics. In other words, the problem is how to compute the inverse kinematics (if working in eccentric coordinates, such as when using visual tracking) or the inverse dynamics (when working in intrinsic coordinates such as when using manipulandum; see Robot Learning and Robot Arm Control).

A large part of robotics research follows a purely engineering perspective, solving assembly task learning from observation (e.g., Friedrich et al., 1996). Typically, the demonstrator's movements are measured either as torques and joint angle displacements through the use of a manipulandum or from visual tracking. The robot is then controlled using classical planning techniques.

More recent efforts, inspired by computational modeling of human imitation, are oriented toward analyzing the underlying mechanisms of imitation in natural systems and modeling those mechanisms in artificial ones. The goal here is to design robot controllers showing similar robustness and adaptability as natural systems. Biologically inspired models of the ability to imitate have been tested in experiments in which the robot could replicate movements of the head and arms of a human (see Schaal, 1999, for a review).

Discussion

Imitation is a concept heavily debated in the biological literature. Modeling can eliminate some of the debate by defining what minimal computation is necessary for each type of imitation. Several theoretical models have been proposed to distinguish between each level of computation, e.g., by differentiating between purely associative imitation (low-level imitation) and sequential imitation (high-level imitation). Although conceptual distinctions are important, they are hard to validate through behavioral studies only. Computational models play a key role in validing these theories by offering an explicit functional description of the computation required for each level of imitation. Realistic modeling that uses real data as input (e.g., video recording of human or animal motion) and physical devices (e.g., robots) or realistic simulation as output is essential to gain a fuller understanding of the mechanisms underlying sensorimotor coordination in imitation.

At this point, there are very few computational or robotic models of imitation. However, the field is currently popular and is bound to grow rapidly within the next years. Its popularity is in part due to recent technological development in robotics that have allowed the design of humanoid robots whose joint complexity approaches that of humans. Modeling of imitation has also benefited from a recent spate of neurological data on human and monkey imitation. Computational and robotic modeling are expected to fill in the gaps between modeling of low-level information (from neurological studies) and modeling of high-level information (from behavioral studies). Modeling of imitation should lead to a better understanding of the neural mechanisms at the basis of social cognition and offer new perspectives on the evolution of animals' ability for social representation.

Roadmap: Cognitive Neuroscience

Related Reading: Action Monitoring and Forward Control of Movements; Grasping Movements, Visuomotor Transformations; Language Evolution, The Mirror System Hypothesis; Motor Primitives; Reaching Movements, Implications for Connectionist Models; Sequence Learning

References

Arbib, M., Billard, A., Iacobonni, M., and Oztop, E., 2000, AQ=4 Mirror neurons, imitation and (synthetic) brain imaging, *Neural Netw.*, 13:953–973.

Billard, A., 1999, Learning motor skills by imitation: A biologically inspired robotic model, *Cybern. Syst.*, 32:155–193.

Byrne, R. W., and Russon, A.E., 1998, Learning by imitation: A hierarchical approach, *Behav. Brain Sci.*, 21:667–721.

Dautenhahn, K., and Nehaniv, C., Eds., 2002, *Imitation in Animals and Artifacts*, Cambridge, MA: MIT Press.

Doupe, A. J., and Kuhl, P. K., 1999, Birdsongs and human speech: Common themes and mechanisms, *Annu. Rev. Neurosci.*, 22:567–631. ◆

Decety, J., Chaminade, T., Grezes, J., and Meltzoff, A. N., 2002, A PET exploration of the neural mechanisms involved in reciprocal imitation, *Neuroimage*, 15:265–272.

DeRenzi, E., Motti, F., and Nichelli, P., 1980, Imitating gestures: A quantitative approach to ideomotor apraxia, *Arch. Neurol.*, 36:6–10.

Dittrich, W. H., 1999, Seeing biological motion: Is there a role for cognitive strategies? in *Lecture Notes in Artificial Intelligence* (A. Braffort et al., Eds.), Berlin: Springer-Verlag, 1739, pp. 3–22.

Friedrich, H., Munch, S., Dillmann, R., Bocionek, S., and Sassin, M., 1996, Robot Programming by demonstration (RPD): Supporting the induction by human interaction, *Machine Learn.*, 23:163–189.

AQ=5

Heyes, C. M., 2001, Causes and consequences of imitation, *Trends Cogn. Sci.*, 5:253–261. ◆

AQ=6

Lhermite, F., Pillon, B., and Serdaru, M., 1986, Human autonomy and the frontal lobes: Part I. Imitation and utilization behavior: A neuropsychological study of 75 patients, *Annu. Neurol.*, 19:326–334.

Meltzoff, A. N., and Moore, M. K., 1999, Resolving the debate about early imitation, in *Reader in Developmental Psychology* (A. Slater and D. Muir, Eds.), Oxford: Blackwell, pp. 151–155. ◆

Rizzolatti, G., Fadiga, L., Gallese, V., and Fogassi, L., 1996, Premotor cortex and the recognition of motor actions, *Cogn. Brain Res.*, 3:131–141.

Whiten, A., 2000, Primate culture and social learning, *Cogn. Sci.*, 24, 2000. ◆

Schaal, S., 1999, Is imitation learning the route to humanoid robots?, *Trends Cogn. Sci.*, 3:233–242. ◆

AQ 1: Author: Pl. add Heyes 1999 to Refs

AQ 2: Author: Sp? Lhermite in Refs ??

AQ 3: Author: 2000 in Refs

AQ 4: Author: 2002 on p. 7

AQ 5: Author: Add Heyes, C. M., 1999,

AQ 6: Author: Lhermatte on p. 6. ??

AQ 7: Author: Pls. provide permission to use this Fig

Figure 1. Robota, a minihumanoid, doll-like robot, can mirror the arm and head motion of a human demonstrator by visual tracking of the optical flow. Researchers are investigating its use as an educational toy for normal and handicapped children. (From Billard in Dautenhahn, K., and Nehaniv, C., Eds., 2002, *Imitation in Animals and Artifacts*, Cambridge, MA: MIT Press, Reproduced with permission.)

---

*Unsuccessful replications of the work led to a large debate that seems now quasi-resolved, thanks to several consecutive successful replications.