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Imitation

4 *Aude G. Billard*

5 Introduction

6 *Imitation*—the ability to recognize and reproduce others' actions—
7 is a powerful means of learning and developing new skills. Species
8 endowed with this capability are provided with fundamental abil-
9 ities for social learning. In its most complex form, imitation pro-
10 vides fundamental capabilities for social cognition, such as the rec-
11 ognition of conspecifics, the attribution of others' intentions, and
12 the ability to deceive and to manipulate others' states of mind.
13 Improved understanding of animals' ability to imitate can contrib-
14 ute to both biological and engineering sciences.

15 Research on imitation builds a bridge between biology and en-
16 gineering, and between the study and use of imitation. Biology
17 seeks to better understand the cognitive and neural processes be-
18 hind the different forms of animal imitation, and how these relate
19 to the evolution of social cognition. Engineering uses studies of
20 the biological processes of human imitation to design robot con-
21 trollers and computational algorithms enabling learning and imi-
22 tative skills similar in robustness and flexibility to human skills.

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

31 Theoretical Modeling

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

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

48 Simple forms of imitation that probably require no understand-
49 ing of intention or theory of mind are found in, e.g., rats and mon-
50 keys (Heyes, 1999). These species' copying ability is generally
51 considered to be an instance of *social facilitation*, in which the
52 correct behavior is prompted by the social context. This simple
53 imitative behavior seems to rely on a form of associative learning
54 that accepts temporal delays, imprecise timing, and incomplete
55 cues. Observation might enhance learning by restricting the asso-
56 ciations to only the sensorimotor pathways that are activated during
57 observation. For example, in rats, pushing the correct lever is as-
58 sociated with odors, not colors, when colors are an invariant across
59 the observed trials.

60 More complex forms of imitation are demonstrated by apes and
61 dolphins. Chimpanzees and orangutans can master simple sequen-
62 tial, manipulatory tasks. They are capable of replicating part of the
63 observed behavior in a different context than that in which it was
64 observed. Dolphins can be trained to copy long sequences of body
65 movements following human demonstration, showing an ability to
66 map different body structures to their own (they respond to the

67 demonstrator's movements of the legs and arms with similar move-
68 ments of their tail, and fins respectively).

69 These more complex forms of imitation are set apart from sim-
70 pler ones because they encompass the ability to reproduce *se-*
71 *quences* of actions and the ability to *transform* the actions so as to
72 produce variations (subparts) of the observed behavior in the same
73 or a different context (see, e.g., Byrne and Russon, 1998; Heyes in
74 Dautenhahn and Nehaniv, 2002).

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

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

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

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

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

122 *Motion Perception*

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

138 *Motor Control*

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

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

156 In summary, evidence from psychophysical studies of motion
157 perception and from motion studies suggest that, to achieve a good
158 replication of movements from a paucity of visual cues, the brain
159 uses models of human kinematics and dynamics of motion. More-
160 over, it is likely that visual and motor representation of movements
161 bear a close relationship for the mapping to be immediate and pre-
162 cise. It is not yet understood how the CNS builds these
163 representations.

164 **Computational Modeling**

165 The challenge faced by computational modeling is to construct a
166 model that can account for all the instances of imitation reported
167 in the literature. The model should provide a means of naming and
168 distinguishing animal imitative abilities, following a list of fun-
169 damental cognitive components. This hierarchical representation of
170 animal imitation should follow the evolutionary tree, such that the
171 different cognitive processes can be linked to the evolution of spe-
172 cific neural structures. We review next the evidence for neural
173 structures specific to imitation.

174 *Neural Structures Behind Visuomotor Imitation*

175 Imitation has been a topic of research primarily in the cognitive
176 and psychological sciences; Only recently has imitation become
177 the explicit topic of a number of neuroscience studies. This new
178 trend started with the discovery of the *mirror neuron* system (Riz-
179 zolatti et al., 1996), a neural circuit in F5 area of monkey premotor
180 cortex that is active both when the monkey observes another mon-
181 key or a human grasping or manipulating objects and when the
182 monkey performs the same manipulation. The mirror neuron sys-
183 tem has been proposed as the link between visual and motor rep-
184 resentation that is necessary to learn from the observation and im-
185 itation of others' actions. Evidence from brain imaging studies
186 (e.g., Decety et al., 2002) suggests the existence of a similar system
187 in humans involving predominantly Brodmann's areas 44 and 45
188 (Broca's areas), 40 (parietal lobe), and 21 (superior temporal
189 sulcus).

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

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

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

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

218 Taken together, evidence from lesion studies and brain imaging
219 suggests a major role for parietomotor connectivity as a basic cir-
220 cuit (possibly the mirror neuron system) behind movement imita-
221 tion, and it also highlights the importance of frontoparietal con-
222 nectivity in regulating this circuit.

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

232 Computational modeling investigates some of the possible im-
233 plications of a high-level representation of movements common to
234 both visual and motor systems (a mirror neuron system) for imi-
235 tation learning. In this quest, Oztop and Arbib developed a com-
236 putational model of monkey mirror neuron system (see Arbib et
237 al., 2002, and LANGUAGE EVOLUTION: THE MIRROR SYSTEM HY-
238 POTHESIS). The model accounts for the role of the parietal lobe and
239 F5 area in recognition and control of grasping. In particular, it gives
240 a description of how, through learning of performing grasps, vis-
241 uomotor (from parietal lobe to F5) connectivity can be built.

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

252 Billard's (1999) model gives a high-level, comprehensive, but
253 simplified representation of the visuomotor pathway behind learn-
254 ing by imitation, from processing real video data to directing a
255 dynamic simulation of a humanoid or an actual robot (Figure 1).
256 The model has composite modules whose functionalities were in-
257 spired by those of specific brain regions, incorporating abstract
258 models of the superior temporal sulcus (STS), the spinal cord, the
259 primary motor cortex (M1), the dorsal premotor area (PMd), and
260 the cerebellum. Each part is implemented at a connectionist level,
261 where the neuron unit is modeled as a *leaky integrator*. Neurons
262 in the PMd module respond both to visual information (from STS)
263 and to corresponding motor commands produced by the cerebel-
264 lum. The STS-PMd-M1 interconnection is a simplified model of a
265 mirror neuron system. The biological plausibility of the model was
266 validated against kinematic recording of human motion (Billard,
267 1999) and functional magnetic resonance imaging (fMRI) data of
268 human imitation of finger motion (Arbib et al., 2002).

269 **Robotics Modeling**

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

276 An important issue dealt with by computational and robotic
277 modeling is that of determining a measure of the similarity across
278 demonstrator and imitator motions (Schaal, 1999; Dautenhahn and
279 Nehaniv, 2002). For instance, when imitating grasping an object,
280 one can reproduce one, a few, or all characteristics of the move-
281 ments, and one can in principle reproduce (1) the goal of the move-
282 ment (grasping the object with any effector following any path),
283 (2) the goal of the movement and the correct effector (grasping the
284 object with the correct hand), and (3) the detail of each joint move-
285 ment, the motion of subsegments, and even the overall speed of
286 movement. In each case, a different measure of the similarity be-
287 tween demonstrator and imitator movements must be used to ac-
288 count for the correctness of the reproduction. The measure should,
289 in some cases, be qualitative, comparing the relationships across
290 objects (which hand, which object), whereas in other cases it is
291 quantitative, comparing the paths followed by each hand or com-
292 paring the angular trajectories of each joint.

293 In construction detailed imitations of joint motion, the problem
294 is how to transfer human motions into robot motions, insofar as
295 humans and robots have very different dynamics. In other words,
296 the problem is how to compute the inverse kinematics (if working
297 in eccentric coordinates, such as when using visual tracking) or the
298 inverse dynamics (when working in intrinsic coordinates such as
299 when using manipulandum; see ROBOT LEARNING and ROBOT
300 ARM CONTROL).

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

307 More recent efforts, inspired by computational modeling of hu-
308 man imitation, are oriented toward analyzing the underlying mech-
309 anisms of imitation in natural systems and modeling those mech-
310 anisms in artificial ones. The goal here is to design robot controllers
311 showing similar robustness and adaptability as natural systems. Bi-
312 ologically inspired models of the ability to imitate have been tested
313 in experiments in which the robot could replicate movements of
314 the head and arms of a human (see Schaal, 1999, for a review).

315 Discussion

316 Imitation is a concept heavily debated in the biological literature.
317 Modeling can eliminate some of the debate by defining what min-
318 imal computation is necessary for each type of imitation. Several
319 theoretical models have been proposed to distinguish between each
320 level of computation, e.g., by differentiating between purely as-
321 sociative imitation (low-level imitation) and sequential imitation
322 (high-level imitation). Although conceptual distinctions are impor-
323 tant, they are hard to validate through behavioral studies only.
324 Computational models play a key role in validating these theories by
325 offering an explicit functional description of the computation re-
326 quired for each level of imitation. Realistic modeling that uses real
327 data as input (e.g., video recording of human or animal motion)
328 and physical devices (e.g., robots) or realistic simulation as output
329 is essential to gain a fuller understanding of the mechanisms un-
330 derlying sensorimotor coordination in imitation.

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

346 **Related Reading:** Action Monitoring and Forward Control of Movements;
 347 Grasping Movements, Visuomotor Transformations; Language Evolu-
 348 tion, The Mirror System Hypothesis; Motor Primitives; Reaching Move-
 349 ments, Implications for Connectionist Models; Sequence Learning

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391 **AQ 1: Author: Pl. add Heyes 1999 to Refs**
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415 **Figure 1.** Robota, a minihumanoid, doll-like robot, can mirror the arm and
416 head motion of a human demonstrator by visual tracking of the optical
417 flow. Researchers are investigating its use as an educational toy for normal
418 and handicapped children. (From Billard in Dautenhahn, K., and Nehaniv,
419 C., Eds., 2002, *Imitation in Animals and Artifacts*, Cambridge, MA: MIT
420 Press, Reproduced with permission.)

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424 *Unsuccessful replications of the work led to a large debate that seems
425 now quasi-resolved, thanks to several consecutive successful replications.
426