Imitation and Priming in Humans, Animals and Machines

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Abstract

This paper gives an overview of research in human and animal imitation mechanisms. The different types of imitative behavior are described as well as the evolutionary reasons for imitation abilities in humans and animals. Known and hypothesized mechanisms behind imitation are also covered. The concepts Goal emulation, Response facilitation and Stimulus enhancement are often confused with pure imitation. The differences are described and discussed followed by an overview of Priming and how it relates to these three concepts. The involved mechanisms are finally described using a modified model for cognitive control, inspired by Miller and Cohen (1994). The model combines concepts from imitation and priming. A similar model for behavior recognition, which is an important part of imitation, is also suggested. It integrates perceptual attention, priming, and cognitive control and addresses the ambiguity problem inherent in demonstrated behaviors. Both models are suggested for implementation and evaluation in a physical robot.

1. Introduction

Imitation can be defined as the copying of various aspects of an observed behavior. While such processes were often dismissed as “mere imitation” in the early days of behavioral sciences, they are now considered sophisticated cognitive capabilities that in fact very few species are capable of. In humans and some animals imitation occurs at very many levels and for a number of different reasons.

Priming is another well studied class of learning mechanisms in which a stimulus influences the response to a related stimulus at a later occasion. This paper starts with an overview of research and results in human and animal imitation in Section 2. Current knowledge on the mechanisms behind imitation and other related concepts are also reported and discussed. Priming, and the relation to imitation related mechanisms, is described and discussed in Section 3. In Section 4, the mechanisms Goal emulation, Response facilitation and Stimulus enhancement are described using a model for cognitive control inspired by Miller and Cohen (1994). The model combines concepts from imitation and priming. In Section 5, a similar model for behavior recognition is suggested. It integrates perceptual attention and cognitive control.

2. Imitation – (not only) a very human activity

As we shall see in the following, the word “imitation” can be given a large number of different meanings. An intuitive first attempt to define the word could be *”instances in which infants reproduce actions or behaviours they have witnessed being produced by another individual”* (Nielsen, & Slaughter 2007). More aspects and variants of the concept of imitation will be given in Section 2.2.

Many imitative behaviors are innate both with humans and animals, see Figure 1. They have been observed in 2-3 weeks old infants (Meltzoff & Moore, 1977), and a study with babies less than 1 hour old reports supporting results. Apart from humans, great apes and birds show a prevalent predisposition to imitate (Zentall, 2006).

Meltzoff (1996, p. 363) has proposed that in the case of human infants, there is an “inbuilt drive to ‘act like’ their conspecifics”. Meltzoff bases his conclusion on data suggesting that infants (and even newborns as shown by Meltzoff and Moore (1989) and also Reissland (1988)) imitate a wide range of adult demonstrated gestures, including lip, cheek, brow, head, and finger movements, as well as emotional expression.

Also neuropsychological findings support the claim that imitation is innate. Mirror neurons are special brain structures that support imitation. These neurons fire both when the animal acts and when it observes the same action performed by another animal (of the same kind). Mirror neurons have been observed in primates (Gallese et al., 1996) and are believed to exist also in humans. While their exact contribution to imitation is still unclear, it is speculated that mirror neurons are important as an interface between perception and action.

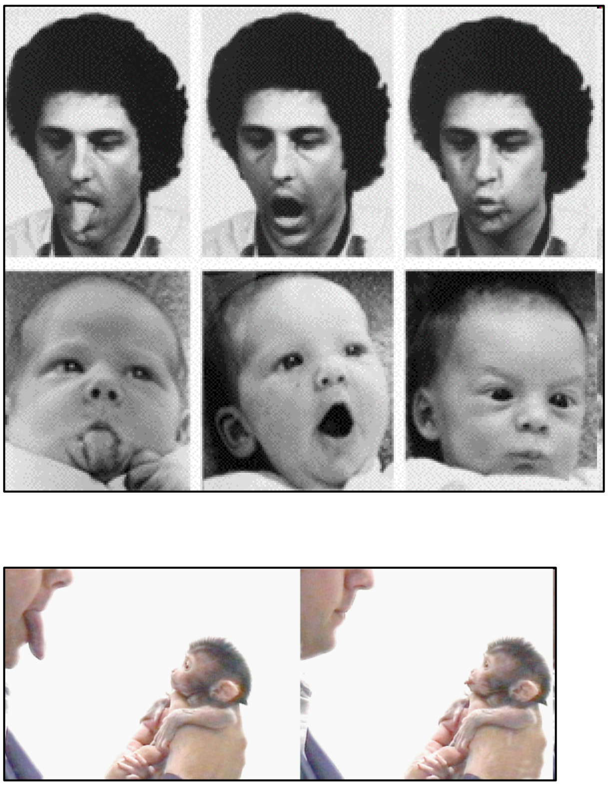

Figure 1. Imitative behaviors are partly innate both with humans and animals. Pictures from (Meltzoff & Moore, 1977).

2.1 Why do we imitate?

It is reasonable to ask why nature has equipped us with a wish and ability to imitate the behavior of others. There are at least two major reasons; Learning and Social interaction:

Imitation may be used as a way to learn new skills, like how to open a box or how to hold a fork. Imitation is sometimes used to tune an existing behavior, e.g. preference for certain food. If a rat encounters two new kinds of food, it will prefer to eat the kind that it has seen another rat eat (Galef, 1988a). Imitating others is much more efficient than trial-and-error since it allows the experience of one individual to be passed on to others. Learning by imitation is also more flexible than fixed innate behaviors (Boyd, & Richerson 1988).

Imitation is also a way to initiate and maintain social interaction (Meltzoff, & Moore 1992). It may be used to develop concepts of self and others. This is important for many reasons, for instance to be able to predict what other individuals will do and will not do. Imitation is also used as a way to indicate recognition of others. As an example, infants link gestures with individuals, and use imitation to signal recognition of those individuals.

2.2 What do we imitate?

Imitation implies gathering information of another individual's behavior by observation. Available sources of information are (Call, 1999):

1. Actions, i.e. body movements.
2. Result, i.e. changes in the environment. This may or may not contain the intended goal.
3. Goal, i.e. the inferred wanted state of the world. Note that while actions and results often are observable, goals most often have to be inferred. However, goals typically provide much more information than the other types of information. By inferring the correct goal, even unsuccessful, irrelevant, and accidental demonstrations can provide enough information (Carpenter, 2006). Furthermore, if the goal is correctly inferred, imitation can also work when there are physical dissimilarities between the demonstrator and the imitator (Nehaniv & Dautenhahn 2001).
4. Reality and context often provide essential information in addition to actions, result, and goal that are extracted from the observed act. Examples of this source of information are given in Section 2.3.2.

In general, animals are good at 1 and 2 (maybe 3 too) while humans may use all four types of information depending on stage of development. The sources of information, alone and in combination, represent classic terms related to the imitation concept:

- *Mimicry* refers to repeating the demonstrator's actions
- *Emulation* refers to learning causal relations between actions and the resulting environment changes by observing. Boesch and Tomasello (1998) write: "In emulation learning learners see the movement of the objects involved and then come to some insight about its relevance to [other] problems". This necessarily involves some "insight" and is regarded as harder than other types of imitative behavior (Call & Carpenter 2001).
- *Goal emulation* refers to an imitative behavior aiming at arriving at a goal state that is inferred from the demonstration. (Whiten and Ham, 1992). The way to arrive to this goal is not necessarily copied from the observation.
- *Imitative learning* refers to a combination of the three types above; i.e. repetition of actions, results, and goal. An additional requirement for "true imitation" is often that the target behavior should not already be part of the observing animal's repertoire (Clayton, 1978).

2.3 How do we imitate?

In short, imitation is all about making sense of what other people do. An understanding of others' intentions and goals are essential for true imitation. Already a 12-18 months old child can do it, but the actual mechanisms are mostly unknown. Two important components in the process are described below.

2.3.1 Theories of mind

A number of *theories of mind* exist in developmental psychology, the most prominent being *Simulation theory* and *Theory theory*. The latter assumes that we have an innate "folk psychology" used to reason about others' minds. This psychology is supposed to contains of a set of causal laws about behaviors. Simulation theory claims that “Human beings are able to use the resources of their own mind to simulate the psychological etiology[1] of the behaviour of others” (Gordon, 1999). The same mechanism is assumed to be used for recognition and generation of behaviors and is therefore often claimed to be involved in imitative behavior. During simulation, the system is ”taken off-line” such that inputs are replaced by “pretend states” and all outputs are suppressed. Simulation theory gained neurophysiological support when so called *mirror neurons* (Rizzolatti & Arbib, 1998) were discovered in some animal brains. These neurons fire both when observing and performing a behavior. See Oztop, Kawato, & Arbib (2006) for more information on how mirror neurons can subserve imitation.

By applying a theory of mind, the actions, goals, and intentions triggering an observed behavior may be inferred.

2.3.2 Reality or context

For all kinds of imitation-like behaviors, raw observed data often is not enough to accurately deduce actions, goals, and intentions. Important additional information may often be extracted from the reality or context in which a performed act is observed.

When to imitate

- *Audible markers* - Infants before age 18 months seem to understand something about the intentions of other persons (Carpenter, Akhtar, & Tomasello, 1998). The understanding is based on interpretations of vocal markers during a demonstration, such as “There”, marking an intentional action, and “Woops”, marking an accidental action. After such a demonstration, infants were given a chance to repeat the action themselves. Infants imitated almost twice as many of the adult’s intentional actions as her accidental ones.
- *Timing of gaze* - In an experiment by Baldwin and Baird (2001), the timing of the gaze is shown to be important to the imitation process. If the demonstrating adult first looks at the attended object and then acts: the action is judged as intentional and will be imitated. If the adult acts first and look only after the operation, the action is judged to be accidental and will not be imitated.
- *Direction of gaze* - In an experiment by Behne, Carpenter, & Tomasello (2006), an adult switched on a light switch with the forearm. This behavior was copied by observing infants only if the demonstrator attended to her action.
- *Who to imitate* - In (Meltzoff, 1995) 18-months infants showed ability to differentiate between human and machine demonstration and attribute intentions only to the human. The experiment also demonstrated how the infants could learn from unsuccessful examples. The infants were shown attempts an adult who "accidentally" slipped several times when trying to pull a toy apart (Figure 2, top), thus the goal state was not achieved. Despite this, the infants tried to achieve the intended goal after the demonstration. However, if the demonstration was performed by a machine, as shown in Figure 2, bottom, the infants did not perceive the goal of pulling the toy apart if the machine demonstrated failed attempts. However, if the machine demonstrated successful attempts, the infant

[1] Etiology is the study of causation, why things occur, or the reasons behind the way that things act.

would imitate that behavior. The attribution of intention or goal is obviously connected to an understanding of the difference between men and machines: "… people's acts can be goal directed and intentional, but the motions of inanimate devices are not; they are governed purely by physics, not psychology" (Meltzoff, 2005).

In another study, 14-month-olds saw a person on television demonstrate target acts with 3-D toys. When they returned to the laboratory the next day, they were handed the toys for the first time. Infants re-enacted the events they saw on TV the previous day (Meltzoff, 1988).

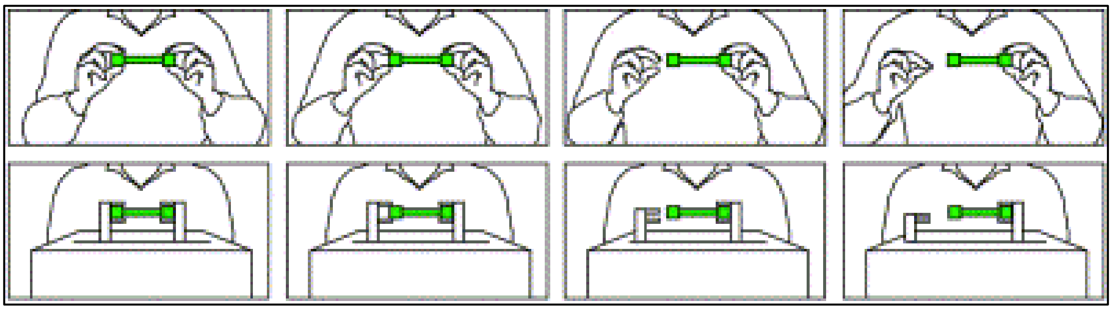

Figure 2. Human demonstrating an unsuccessful act (top) and an inanimate device doing the same movements (bottom). Observing infants attribute goals and intentions to the human but not to the inanimate device. Picture from (Meltzoff, 1995).

Identification of goals

Information that helps in understanding of intentions and goals is often provided by the physical context in which the observed act takes place:

Bekkering et al. (2000) showed 3- to 6-year-old children an adult touching a table in two locations in turn. In case 1, there were dots on the table in those locations and in case 2 there were no dots. In case 1, children touched the same locations as the adult but did not match the exact arm positions since the goal was clearly identified as touching the dots. In case 2, children usually copied the behavior exactly, even the crossed or straight arms because no other could be identified.

A related example, given by Carpenter, Call, & Tomasello (2005) shows how 18-months old infants interpret the goal of a demonstration of moving a toy mouse toward a location with a hopping/sliding motion differently depending on if there is a toy house at the end location or not. If there is no house, the infant copies the hopping/sliding. With a house, the infant imitates by simply moving the mouse to the house.

In (Gergerly, Bekkering, & Király 2002), 14-month-olds were shown to engage in "rational imitation". The infants watched an adult placing her hands on a table, bending over and pressing a switch with her forehead to illuminate a light box. When given a chance to play with the box, many infants used the same technique to illuminate the light. However, if the adult's hands were occupied during the demonstration, most infants used the more normal method of pressing the light with their hands. Hence, by 14 months of age infants make use of an advanced understanding of others' intentions and goals.

2.4 Phenomena confused as imitation

Imitation is essential for humans and is also found in several animals. However, in many cases, we can explain the behavior with simpler mechanisms than imitation. Three such mechanisms are Response Facilitation, Stimulus Enhancement, and Goal Emulation (Byrne, 1994). Examples of observed behaviors that have been described as true imitation but could as well be combinations of the three mechanisms above are when pigeons learn to operate a food apparatus and when chimpanzees use a ”hammer” and also do ”ant fishing”.

2.4.1 Response Facilitation

This mechanism refers to how observing a response enhances the memory representation of the response and how this in turn increases the probability of the response to be subsequently repeated by the observer. To be denoted Response facilitation, the response already has to be in the animal’s repertoire. The mechanism is often combined with a reward. Sometimes this causes unexpected effects, such as when a satiated animal in the presence of food resumes eating upon the introduction of a hungry animal which begins eating (Tolman, 1964). Response facilitation does not always have to involve attraction. One example is when children acquire their parents fear, e.g. irrational fear of spiders (Byrne, 1994).

2.4.2 Stimulus Enhancement

Stimulus Enhancement refers to how seeing some act done in a particular place or to some particular object increase the observer’s probability of going to that place or interacting with that object (Spence, 1937). Numerous cases, once claimed to show imitation, have proved to be explicable as stimulus enhancement (Galef, 1988). Stimulus enhancement serves as a useful learning mechanism since behavioural exploration may be concentrated upon a narrowed range of stimuli. This clearly increases the chance of discovery of the means of achieving a given goal.

Suppose a monkey observes another monkey eating under a coconut tree. Stimulus enhancement focuses the observing monkey’s attention on the large nuts on the ground under the tree and; it begins to experiment with the nuts and discovers how to crack them open, using actions in its own repertoire; and it will consequently learn more quickly and successfully than if it had come upon the coconut tree alone. It may happen to end up using the same technique as the other monkey, but not because the other monkey showed it.

In combination with response facilitation stimulus enhancement may become very powerful. An animal observes another animal performing a particular act to a certain object, in a certain place and gaining food in the process. The observing animal is then more likely to go to the same place and perform the same act on the same object. This is not regarded are true imitation, primarily because the act already has to exist in the animal’s repertoire.

2.4.3 Goal Emulation

The term "goal emulation" (Whiten & Ham 1992) is used for situations when one animal copies the goals or outcomes of another animal's behaviour. However, the way to achieve the goal is not copied. An example is when a child sees a foot ball kicked into goal and wants to copy this result, but uses its own idiosyncratic way of hitting to do so. Another example is illustrated in Figure 3. In experiments reported in (Taylor & Saayman, 1973), an infant dolphin observed a human blowing cigarette smoke at the pool’s glass. The dolphin swam to its mother, returned and released a mouthful of milk giving a similar effect as the cigarette smoke. The goal was copied but not the means to achieve it.

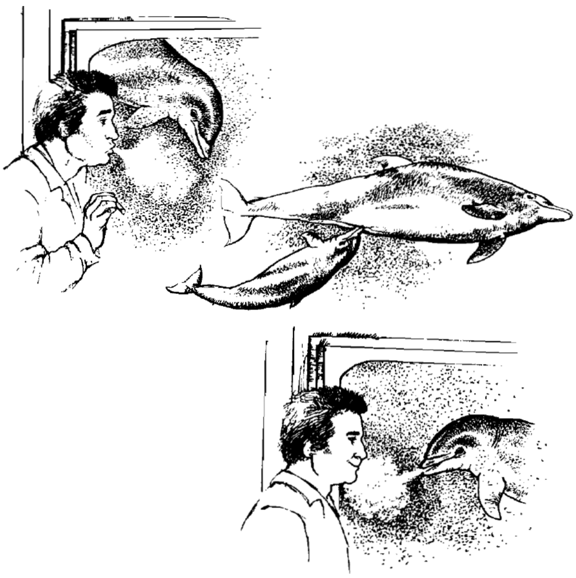

Figure 3. In studies by Taylor & Saayman (1973), a baby dolphin blows milk to mimic the human’s puff of cigarette smoke. That is, it copies the inferred goal of the observed behavior. Picture from (Byrne, 1994).

Under some circumstances, a demonstrating individual need not even be present for stimulus enhancement and/or goal emulation to be in effect, as exemplified by Byrne & Russon (1998): “Simply finding coconuts beneath a certain tree, cracked open but still containing a little flesh, may increase the salience of the location and features of coconuts (stimulus enhancement), or stimulate the aim of eating coconut meat (goal emulation)”.

Byrne (1994) emphasizes that the three mechanisms discussed above can “not give rise to novel and complex sequences without trial-and-error learning”. However, “imitation may occur to greater effect when influenced by these simpler mechanisms”.

3. Priming

Priming is a term used to denote a number of different mechanisms in which exposure to a stimulus influences the response to a related stimulus at a later occasion. Depending on the meaning of the word "related", two main categories of priming can be defined:

In *Perceptual priming*, the form of the stimulus is of importance. For example, when a subject reads a list of words including the word *table*, and is later asked to complete a word that starts with *tab*, the initial presentation of *table* primes the subject to answer *table*. Another example is a subject's ability to recognize distorted pictures. If non-distorted pictures of one object have been previously shown, distorted pictures of the same or similar objects are more easily recognized. Perceptual priming exists for many sensor modalities, for instance visual, auditory, and haptic even if most research deals with visual priming, in particular related to word reading tasks. Priming has been reported also for unconscious perception, even for information presented auditorily during anesthesia (Kihlstrom, & Schacter, 1990) and visually (Bar & Biederman, 1998).

In *Conceptual priming*, the meaning of the stimulus is of importance. For example, reading the word *table* makes it more likely to use words like *chair* and *sofa* in later occasions, because *table* and *chair* belong to the same category. Conceptual priming does not depend on sensor modalities; pictures can for example conceptually prime sounds. Conceptual priming is thought to involve activation of concepts stored in semantic memory. Semantic memory refers to the memory of meanings, understandings, and other concept-based knowledge. It includes generalized knowledge that does not involve memory of a specific event.

Early models of Semantic memory used *Semantic networks* (Collins & Quillian, 1969). Each node is a word, representing a concept like "Car" or "Can move", see example in Figure 5. Each node is connected to other nodes by links representing various kinds of relations e.g. *is, isa, has, can*. For instance, "Car" could be linked towards "Vehicle" by an *isa* link and towards "Door" by a "has" link. When a node becomes active, e.g. by a perception mechanism, that activation spreads to other nodes via the links between them by a mechanism called Spreading activation (Collins & Quillian, 1972). The model has been expanded by associating weights with the links (Collins & Loftus, 1975). The distance between two nodes is determined by semantic relatedness. Related concepts (e.g. "House", "Expensive") are stored close together in memory. Unrelated concepts (e.g. "Vehicle", "Shop") are stored far away. Conceptual priming may be described by semantic network models: you are more likely to retrieve information from memory if related information has been activated a short time before.

Conceptual priming can be based not only for basic object categories but also for higher-level concepts such as in *Structural Priming*. Chang et al. (2000) describes the following experiment in which a subject is shown two pictures in sequence. A person who describes the first picture by *"The girl showed a picture to the teacher"* tends to describe the second picture (see Figure 4) by *"The boy is giving a guitar to the singer"*.

Figure 4. Picture from an experiment on Structural priming (Bock, 1986).

In contrast, a person who describes the first picture by *"The girl showed the teacher a picture"* tends to describe the shown figure by *"The boy is giving the singer a guitar"*. Priming does in this case lead to a tendency to use similar syntactic structures in successive clauses or sentences (Bock, 1986).

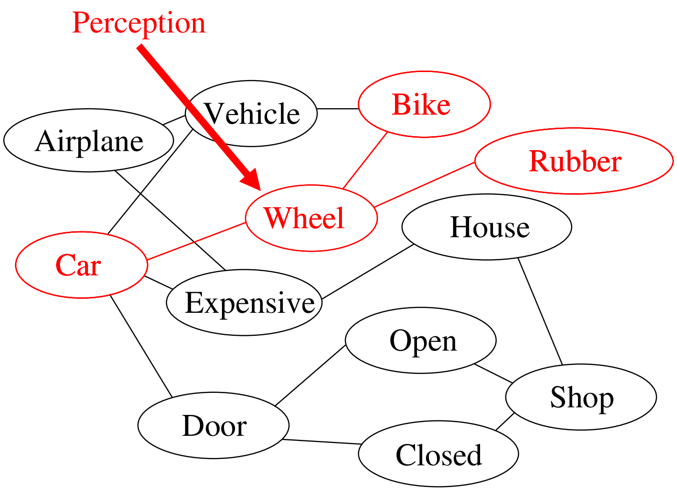

Figure 5. Semantic network model of semantic memory. Lengths of links represent semantic relatedness. When a node is activated, e.g. through perception, the neighboring nodes become activated by Spreading activation.

Other common models for semantic memory use Prototype or Similarity-based approaches or neural networks to represent categories, attributes, and relations. For an excellent in-depth overview of these models refer to Rogers (2006).

3.1 Generalized Priming

In Section 2.4, the mechanisms Goal emulation, Response facilitation and Stimulus enhancement were described. Byrne (1994) and Byrne & Russon (1998) argue that they can all be described as Priming in a general sense. In all three cases, *activity levels* of brain records (percepts, actions and goals) are modified by a priming mechanism such that future behavior is affected. This connection is in accordance with Schaal's (1999) description of stimulus enhancement: *Stimuli in the environment that co-occur with the actions of the teacher increase the observer's activation of corresponding internal representations in memory. Consequently, the observer's exploratory behavior will be biased by these activations towards receiving similar stimuli.*

For the following discussion, we need to be more specific and therefore break down the priming concept into two separate phases. Phase 1 constitute the various mechanisms that modify activity levels of brain records. These mechanisms are connected to perception, action, and higher level cognitive functions such as goal identification and behavior recognition. Phase 2 is the cognitive activity that makes use of the modified activity levels. In the case of Stimulus Enhancement this activity is the motor schema supporting motion to or interaction with the primed object. In Response Facilitation, the activity is the observed and subsequently primed response, which is more likely to be performed after it has been already observed. In Goal emulation, the activity is the (unspecified) act of fulfilling the inferred goal.

4. A model combining Priming and Cognitive Control

We will now show how Goal emulation, Response facilitation and Stimulus enhancement, expressed as special cases of priming, can be explained using the model for cognitive control introduced by Miller and Cohen (1994). See also (Hellström 2009).

The model will be described by an example in which an ape is learning to find, crack and eat coconuts. The process is divided into two phases corresponding to the two mechanisms of priming identified above. During phase 1, the animal is mainly observing and following others and conducts a trial and error behavior. The following mechanisms are in operation: Stimuli Enhancement increases the Activity level of Tree and Nut when these objects are seen by the ape while observing someone trying to find food and eat it. This involves advanced perception in which raw data from the eyes are processed and classified[2]. For sake of clarity, this process is not included in the Figure 6, but can be seen in the model for visual saccading in Hellström (2009). Goal emulation increases the Activity level of the goal Open nut when the ape observes another ape opening a nut. This requires Goal identification which is a high-level skill assumed to available as an execute function. Response Facilitation increases the Activity level of the Crack behavior (which is innate). Response facilitation involves high-level behavior recognition which is also assumed to be available as an execute function.

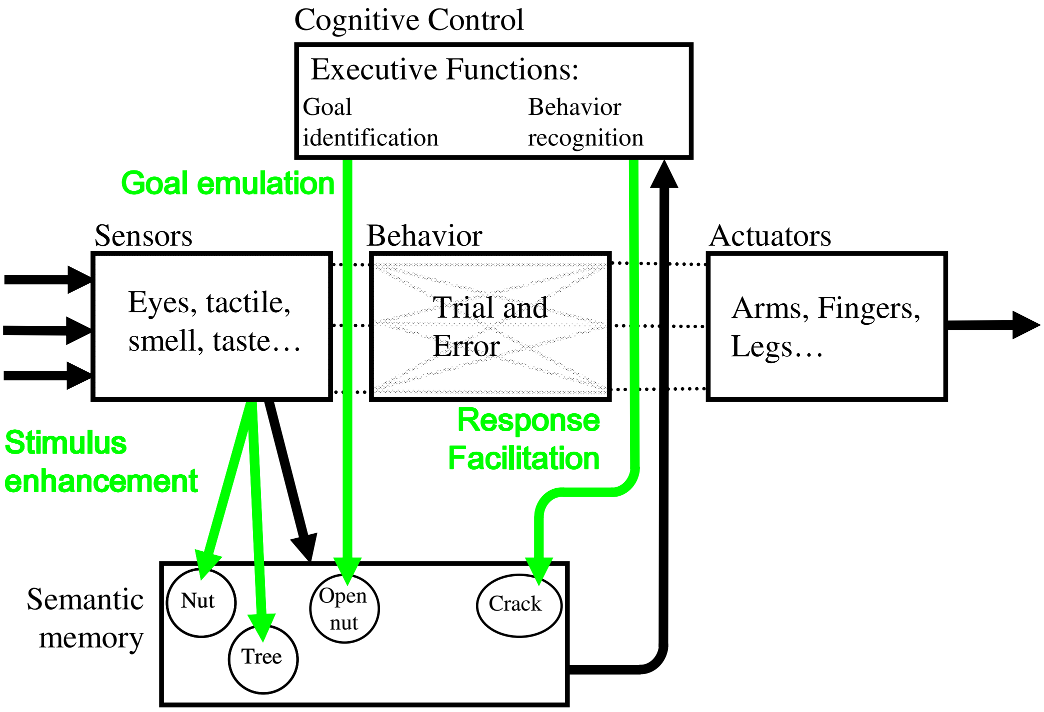

Figure 6. Phase 1 in the cognitive control model for Goal emulation, Response facilitation and Stimulus enhancement. Stimulus enhancement primes memory records corresponding to the Nut and Tree concepts. The identification of Goal and Behaviors are high-level operations that perform priming as Goal emulation (Open nut) and Response facilitation (Crack) respectively.

[2] This kind of pre-processing has been observed in pre frontal cortex (PFC) in monkey's brains as reported in Miller (2003).

In Phase 2, the primed memory records will affect the animal's behavior. The animal is assumed to have no knowledge of a successful feeding behavior, and the *Behavior* block contains competing innate primitive behaviors such as various kinds of taxes and manipulation behaviors. Without an informed cognitive control, the animal's behavior would be a random choice among these innate behaviors. However, the primed memory records from Phase 1 introduce a lot of bias in the executive function responsible for the selection of behavior. The taxis capable of guiding the animal to a tree will have a higher probability to be chosen thanks to the Stimulus enhancement priming the *Tree* item. A pick up primitive will be activated thanks to the Stimulus enhancement priming the *Nut* item. Thanks to the primed *Crack* item, cracking behavior will then have a high probability to be chosen. If this fails, the inferred goal *Open nut* may cause the executive functions to pick another behavior that is associated with to nut opening.

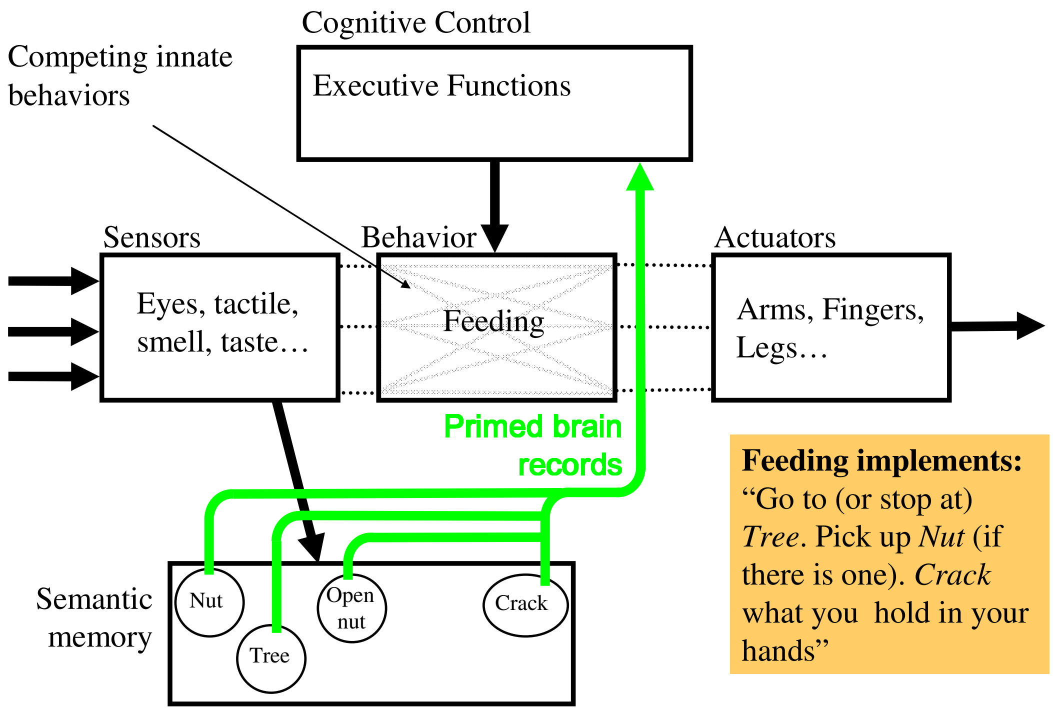

Figure 7. In Phase 2 of the priming mechanism, the primed memory records are used to instantiate and activate innate behaviors such as tropisms (that act as attractive forces towards certain stimuli) or other innate behaviors (such as *Crack*).

It should be noted that Phase 1 and 2 in the general case not necessarily have to run in sequence but also in parallel. Updating of memory records proceeds in such case even during execution of the main behavior (*Feeding* in the example). Suggested further research is to implement and evaluate the discussed model on a physical robot.

It is important to note that the executive functions *Goal identification* and *Behavior recognition* both require cognitive skills with a complexity at the same level of magnitude as the behaviors *Goal emulation* and *Response facilitation* that the model aims at explaining. *Behavior recognition* will be the target for modeling in the next section.

5. A Model for Behavior Recognition Combining Priming, Perceptual Attention and Cognitive Control

Inspired by the model above, a cognitive control model for behavior recognition will now be introduced. The model is quite general and should be applicable to a large number of other cognitive tasks. We will start with a brief introduction to behavior recognition.

Learning from demonstration (LFD) is a robot learning technique that relates to human and animal imitation as described earlier in this paper. A human demonstrates a wanted behavior by tele-operating the robot. After some analysis, the robot should then be able to repeat the demonstrated behavior. Behavior recognition is a key function in many implementations of LFD (Billing & Hellström 2008). While being a hard task in itself, it often gets further complicated by inherent ambiguities in the demonstration. Consider for example the task of moving a robot arm to a box in an environment filled with combinations of red and green boxes and cylinders. From a single demonstration in which the robot arm is tele-operated to a red box it is impossible to infer the intention or goal of the task. Expressed with a behavior primitive *MoveTo(color, type)*, the demonstration may be interpreted in four ways; *MoveTo(C,T)*, *MoveTo(Red,T), MoveTo (C, Box), MoveTo (Red,Box). C* and *T* denote "wild cards" matching any valid value for color and type respectively. For instance, the first interpretation corresponds to the goal *Move to any type of object of any color.* For further information refer to (Billing & Hellström, 2009). To resolve the ambiguity, more information is needed. By repeating the demonstration, now targeting a red cylinder, the uncertainty regarding object type is removed. Both cylinders and boxes seem to fit the intended goal for the demonstrated behavior. A plausible hypothesis therefore is *MoveTo(Red,T)*, i.e.: *"move to a red object of any type"*. Obviously, with more parameters and possible values, the ambiguity can not be resolved by a reasonable number of demonstrations. The proposed model approaches the problem by incorporating perceptual attention to serve as additional bias in the behavior recognition process. To get a feeling for the general idea, consider for instance how stimulus enhancement could have introduced a general pre-disposition for red objects in the robot. This, in combination with the first demonstration, would guide the robot to select the same hypothesis *MoveTo(Red,T)*. Note that the robot not necessarily infers the "correct" goal (i.e. the intention of the demonstrator) with too limited information. However, the process is believed to mimic human decision making in a fairly general and powerful way.

The complete model will now be described in more detail with reference to Figure 8. The robot senses the environment through its sensors and performs pre-processing such as feature detection and data compression. A number of mechanisms are responsible for perceptual attention. They all increase the pre-disposition for perceived concepts; objects, actions, modalities, features, instances in time, etc. Perceived concepts are in this way assigned attentional values as part of their representation in memory. Just as in the model in the previous section, semantic memory is involved to represent abstract concepts such as categories, feature types, and feature values. For concepts more directly referring to current sensed data, short-time memory is a more suitable description of how concepts and corresponding attentional values are kept in memory. The perceived concepts and their associated attentional values are in any case accessible to the executive function where they act as bias in the behavior recognition process. The aim is to select one out of many available hypotheses competing in long-term memory. For the simple example given above, four such hypotheses or interpretations exist. The general idea is that the attentional values will provide additional information (bias) such that some hypotheses are preferred for others. In the example, the two demonstrations both increase the attention for the concepts *Red* while *Box* and *Cylinder* both end up with somewhat lower attentional values (in the Memory box in Figure 7, concepts are written with font size proportional to the attentional value). This bias results in the hypothesis *MoveTo(Red,T)* being selected and placed in memory to be available for the overall LFD process.

The block Perceptual attention represents a variety of possible mechanisms such as:

- *Regular perception* increases the attention of perceived objects. Attentional values are set as a direct result of the demonstration. Multiple, slightly different, demonstrations update the values such that generalization can take place (such as in the example above).
- *Abstract concepts* identified in the perception process, such as categories, feature types, and feature values, are assigned attentional values and placed in semantic memory.
- The *spreading activation* mechanism in similarity-based memory models of semantic memory, such as the one described in Section 3, makes attentional values leak to related concepts.
- *Priming mechanisms*, such as the ones modeled in Section 4, can be seen as attentional mechanisms working at a long time scale. They influence attentional values at a short time scale by spreading activation.
- Internal *reinforcement signals* that co-occur with a fresh percept affect how much the corresponding attentional value is increased.
- Many learning mechanisms directly controls attentional values of sensed information, for instance *Audible markers*, *Direction of gaze*, and *Timing of gaze* (refer to Section 2.3).
- *Habituation*, which causes reduced response to a frequently presented stimuli (Sokolov, 1963), and *Sensitization* which causes increased response to a frequently presented stimuli.

Attentional values should be subject to forgetting mechanisms, with different time constants depending on memory type. Suggested research is to further develop, implement and evaluate the discussed model on a physical robot.

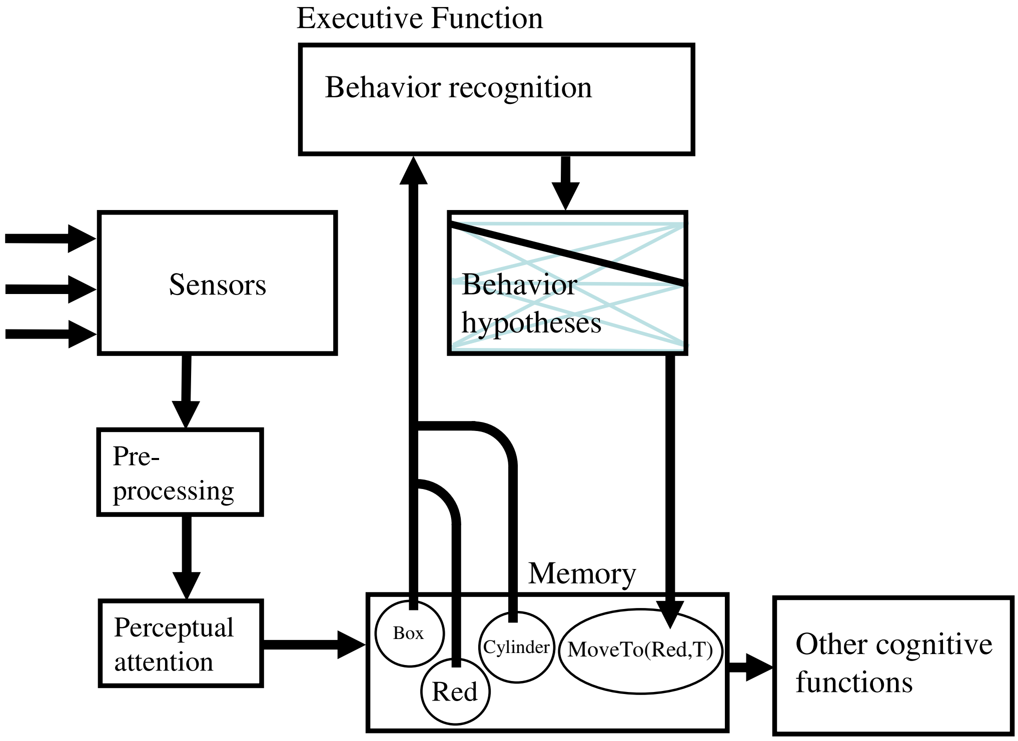

Figure 7. Cognitive control model of behavior recognition. Attentional values for entities in memory act as bias in the behavior recognition process.

References

Baldwin, D. A., Baird, J. A., Saylor, M. M., & Clark, M. A. (2001). Infants parse dynamic actions. Child Development, 72, 708-718.

Bar, M. & Biederman, I. (1998). Subliminal visual priming. *Psychological Science* 9 464-469.

Behne, T., Carpenter, M., & Tomasello, M. (2006). From Attention to Intention: 18-month-olds use Others' Focus of Attention for Action Interpretation, The annual meeting of the XVth Biennial International Conference on Infant Studies, Westin Miyako, Kyoto, Japan.

Billing, E. A., & Hellstrom, T. (2008). Behavior recognition for segmentation of demonstrated tasks. In Proceedings of the IEEE International Conference on Distributed Human-Machine Systems, Athens, Greece, pp. 228-234.

Billing, E. A., & Hellstrom, T. (2009). A Formalism for Learning from Demonstration, Submitted to Journal of Intelligent and Robotic Systems.

Bock, J. K. 1986. Syntactic persistence in language production. Cognitive Psychology, 18, 355-387.

Boyd, R., & Richerson, P. J. (1988), An evolutionary model of social learning: The effect of spatial and temporal variation. In T. R. Zentall & B. G. Galef, Jr. (Eds.), Social learning: Psychological and biological perspectives, pp. 29-48. Hillsdale, NJ: Erlbaum.

Byrne, R. W. 1994 The evolution of intelligence. In Behaviour and evolution (ed. P. J. B. Slater & T. R. Halliday), pp. 223–265. Cambridge University Press.

Byrne, R. W., & Russon, A. E. (1998). Learning by imitation: a hierarchical approach, Behavioral and Brain Sciences, Vol. 21, No. 5. (October), pp. 667-721.

Boesch, C. & Tomasello, M. (1998). Chimpanzee and human cultures. Current Anthropology, 39, 591-614.

Call, J. (1999). Levels of imitation and cognitive mechanisms in orangutangs. In S.T. Parker, R.W. Mitchell & H.L. Miles (eds.). Mentalities of gorillas and orangutans (pp 316-341). New York: Cambridge University Press.

Call, J. & Carpenter, M. (2001). Three sources of information in social learning. In: Imitation in Animals and artifacts (Ed. by Dautenhahn, K.): MIT Press.

Carpenter, M. (2006). Instrumental, social, and shared goals and intentions in imitation. In S. J. Rogers & J. Williams (Eds.), Imitation and the development of the social mind: Lessons from typical development and autism (pp. 48-70). New York: Guilford.

Carpenter, M., & Call, J. (2007). The question of 'what to imitate': Inferring goals and intentions from demonstrations. In K. Dautenhahn & C. Nehaniv (Eds.), Imitation and social learning in robots, humans and animals: Behavioural, social and communicative dimensions (pp. 135-151). Cambridge: Cambridge University Press.

Carpenter, M., Akhtar N., & Tomasello, M. (1998). Fourteen- through 18-month-old infants differentially imitate intentional and accidental actions, Infant Behavior and Development, Volume 21, Number 2, 1998 , pp. 315-330(16).

Chang, F., Dell, G., S., Bock, K., & Griffin, Z., M. (2000). Structural priming as implicit learning: A comparison of models of sentence production, Journal of Psycholinguistic Research, 29, 217-230.

Clayton, D. A. (1978). Socially facilitated behavior. Quarterly Review of Biology, 53, 373-391.

Collins, A. M. & Quillian, M. R. (1972). How to make a language user. In E. Tulving & W. Donaldson (Eds.), Organization of memory (pp. 309-351). New York: Academic Press.

Collins, A. M. & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior, 8*, 240-247.

Collins, A. M. & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review, 82(6)*, 407-428.

Demiris, Y., Johnson, M. (2001). Simulation theory of understanding others, In: Imitation in Animals and artifacts (Ed. by Dautenhahn, K.): MIT Press.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. Brain 119:593-609.

Gergely, G., Bekkering, H., & Király, I. (2002). Rational imitation in preverbal infants. Nature, 415, 755.

Hellström, T. (2009). Attention and Cognitive Control in Humans, Animals and Machines, Technical report Department of Computing Science, Umeå University, Umeå, Sweden.

Kihlstrom, J. F., Schacter, D.L. (1990). Anesthesia, amnesia, and the cognitive unconscious. In Memory and Awareness in Anesthesia. Edited by Bonke B, Fitch W, Millar K. Amsterdam: Swets & Zeitlinger, pp. 21-44.

Meltzoff, A. N. and Moore, M. K. (1977). Imitation of Facial and Manual Gestures by Human Neonates, Science, 198, pp. 75-78.

Meltzoff, A. N. (1988). Imitation of televised models by infants. Child Development, 59, pp. 1221-1229.

Meltzoff, A. N., & Moore, M. K. (1992) Early imitation within a functional framework: the importance of person identity, movement and development, Infant Behaviour and Development, 15, 83-9.

Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactment of intended acts by 18-month-old children. Developmental Psychology, 31, 838-850.
Meltzoff, A.N. (2005). Imitation and other minds: The "Like Me" hypothesis.
In S. Hurley and N. Chater (Eds.),to Social Science (Vol. 2, pp. 55-77). Cambridge, MA: MIT Press.

Rizzolatti, G., Arbib, M. A. (1998). Language within our grasp. Trends
in Neuroscience, 21, pp. 188–194.

Nielsen, M, & Slaughter, V. (2007). Multiple motivations for imitation in infancy. In K. Dautenhahn & C. Nehaniv (Eds.), Imitation and social learning in robots, humans and animals: Behavioural, social and communicative dimensions, pp. 343-359. Cambridge: Cambridge University Press.

Oztop, E., Kawato, M., & Arbib, M. (2006). Mirror neurons and imitation: a computationally guided review. Neural Netw., Vol. 19, No. 3. (April 2006), pp. 254-271.

Rogers, T. T. (2007). Computational models of semantic memory. The Cambridge Handbook of Computational Psychology (Edited by Ron Sun), Chapter 18, pp. 226-266.

Schaal, S. (1999). Is Imitation Learning the Route to Humanoid Robots?, Trends in Cognitive Sciences, Vol. 3, No. 6. , pp. 233-242.

Taylor, C. K., Saayman, G.S. (1973). Imitative behavior by Indian Ocean bottlenose dolphins (Tursiops truncatus) in captivity. Behavior, 44(3/4): 286-296.

Whiten, A., & Ham, R. (1992). On the nature and evolution of imitation in the animal kingdom: reappraisal of a century of research. In: Advances in the study of behavior, Vol. 21, Ed. P. J. B. Slater, J. S. Rosenblatt, C. Beer, & M. Milinski, pp. 239-283. New York: Academic Press.

Zentall, T. R. (2006). Imitation: definitions, evidence, and mechanisms, Animal Cognition 9, 335-353.