

Observational Versus Trial and Error Effects in a Model of an Infant Learning Paradigm

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Abstract. We present results from a paradigm of infant motor skill learning, involving selecting the correct approach to grasp a ball placed on a low stability stand. We also construct a theoretical model, based on the concept of observational learning as the discovery of non-perceived affordances and the transfer of actions on affordances, which can explain some of the experimental data presented. We discuss the underlying concepts of the model (including its basis in neuroanatomy) and how they relate to the paradigm, and suggest possible model extensions.

1 Introduction

Imitation and observation are key components of learning in humans and other species. Recent experimental results suggest that one of the components of observational learning may be the transfer of actions on affordances (meaning that known parts of a motor repertoire become associated with “new” affordances, we will discuss this further later), and the discovery of non-perceived affordances. A very broad definition of affordances is that they provide information about how to interact with objects, so learning actions on affordances is a critical part of development.

1.1 Observational Learning

The capacity to learn by observation has important survival value. Trial and error learning is very inefficient and potentially dangerous in situations where the cost of failure is high or it is important to learn rapidly. Learning by observation, however, provides the opportunity to rapidly transfer existing knowledge. Imitation and observation also seem to be closely connected with how we learn languages.

Recent experiments on both human and monkey subjects have shown that during observation of certain actions there is extensive brain activation in areas usually thought to be involved only with the production of those actions [1]. These results suggest the hypothesis that understanding and recognition of observed actions recruits brain areas involved in producing those actions, possibly for mental simulation.

1.2 Affordances

The concept of affordances has considerable value in the study of interactions with objects. Gibson's original definition of affordances was "What [the environment] offers the animal, what it provides or furnishes, either for good or ill." [2] For the purposes of this study, we will define an affordance to be "the set of features of an object that are required to be known before a particular goal based action can be taken on it". The action used by the actor to fulfill that affordance is the affordant action or alternatively, the action on that affordance. The affordances are properties of the objects, which may or may not be known to the observer (see the next section), while the affordant actions are part of the actor's motor repertoire.

One interesting question is that of how initial affordances are "learned". In the Gibsonian view, affordances are part of the properties of the interaction between actor and object, and therefore are not learned. However, under this point of view we can distinguish between "perceived" and "non-perceived" affordances. Non-perceived affordances are those that are possible given the state of the object, but not known to the actor because the actor does not recognise the affordance. We define a perceived affordance to be an affordance known to the observer, and non-perceived affordance to be a potentially learnable affordance for the observer, given either increased motor skill repertoire or discovery of environmental circumstances.

Associating actions with affordances. As well as the discovery of non-perceived affordances, there is the question of how we learn to associate actions with affordances. In situations where the action in question is already part of the observer's motor repertoire, this involves learning to use an existing action on an affordance not already associated with the action. By observational learning, this requires the observer to recognise the action used, involving both the mechanical characteristics (such as contact points of a grip), and the affordance it is used on, then to associate the two.

Various imaging studies have shown that observation of the actions of others activates considerable areas of the brain previously thought to be used only in the production of actions [1]. It is possible that this occurs due to attempts to understand the observed actions by a process of mental simulation, which uses many of the same pathways as production of actions.

1.3 Model Hypotheses and Construction

As we will show later, one of the things infants appear to be learning by observation is the objects' affordances and the way to act upon them. Transfer of affordances to novel objects/situations by observation would provide a powerful learning mechanism. We therefore present a hypothesis on which we base our model:

That one component of observation learning is the discovery of affordances and of the means to act upon them. Another way of looking at this is that actions on affordances (or action/affordance pairs) are learned.

Effectively what is being learned is the observer's knowledge of the affordances available to it (the discovery of unperceived affordances), and the actions to use on those affordances (and the linking of action-affordance pairs).

To model the process of transfer of the means to act upon newly discovered affordance, our model needs to incorporate the following components:

- Some initial set of affordances and actions.
- A system for recognising the affordances acted upon by the observed actor and associating the actions used with that affordance and the task.
- Recall of the action used and integration of this information into a motor plan.

In addition, to be able to consider the parallel mechanism of trial and error learning, the model also needs to include some form of motor error monitor and system to correct motor errors.

2 Paradigm and Model

We now turn to look at developing the model and applying it to experimental paradigms.

2.1 The Simulation Model

Our model comprises several components. These are:

Vision. This represents the basic visual input available to the model. We model this in an extremely simple manner - the region has dedicated nodes each of which holds a possible view available to the model, and they are activated depending on the simulation setup. The possible views represent the initial setup (the ball on the stand), the ball grasped, and the ball knocked off the stand.

Goals. Here the simulation's current goal is stored and used to influence behaviour. In the simple paradigm we present here, the only possible goals are to grasp the object or push it over. Goals are represented by dedicated nodes that code for an action and an object (i.e grasp-ball/push-ball). In the brain, these are coded in separate areas, but we simplify here.

Object representation. This module picks out object features to identify objects. In our simple simulation, the only possible object to be recognised is a ball. The weights of the projections from the vision module are chosen so that feature nodes present here can be activated, which then project to the object codes module where individual objects are represented.

Object codes. Here objects already known to the system are stored, such that they can be activated by the object representation module.

Stored affordance/action pairs. This contains the set of affordances and related actions known to the system. These are primed by the object codes module based on existing learning. The module contains nodes representing

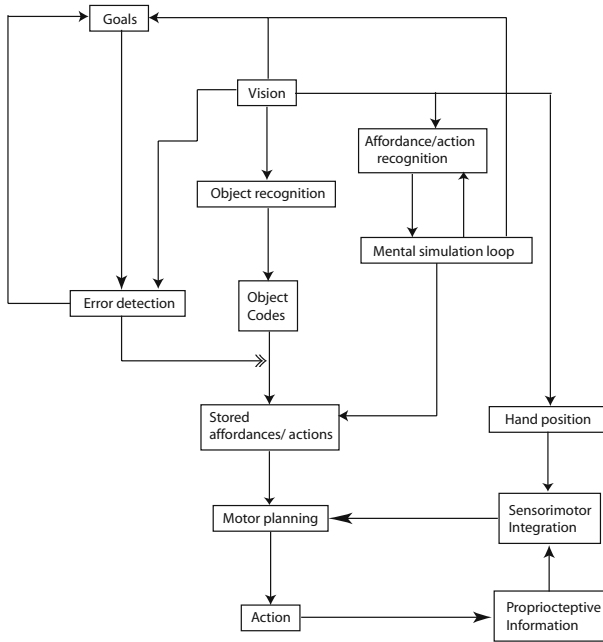


Fig. 1. Modular architecture for execution of grasping actions

actions, and nodes representing affordances, and the connections between these are plastic, such that they can be learned by a Hebbian learning mechanism (concurrent activation of an affordance and an action causes an increase in the connection between them).

Sensorimotor integration. Here proprioceptive information about the current state of the system's hand is fused with visual information to update the motor plan.

Motor planning. Here the affordance information is combined with sensorimotor information about current physical state, to form a motor plan. This involves calculating movements necessary to bring current finger positions to contact points, give the angle of approach.

Action. This module represents the current action the system is attempting to perform, consisting of dedicated nodes. We code the possible approaches to the ball as separate actions.

Proprioceptive feedback. Here the action taken by the system is converted into feedback about the current state of the system's arm/hand. Proprioceptive feedback is coded as a vector update indicating the change in hand position.

Affordance/action recognition. The module processes visual input to attempt to extract information representing the features of an observed affordance and the action used on that affordance, coding here is the same as in the stored action/affordance pairs module.

Affordance/action comparison. Here a candidate action/affordance pair can be compared to the system's stored list of affordances and actions to see whether a match occurs. It works with the recognition and storage systems for affordances and actions to compare and find closest matches.

Mental simulation loop. This module extracts the goals of observed affordance/action pairs by mental simulation - effectively planning out the observed action to determine which goals are associated with it. The module contains a simple internal forward model which simulates use of the action, to determine variables associated with the action that are not directly observable, in particular the action goal (which is part of the affordance to be recognised).

2.2 Experimental Paradigm – The Ball and Stand

We now apply our model to a specific paradigm to test observational learning. In this paradigm, infants are presented with a ball (40 mm in diameter) placed on a support with a narrow base, such that the ball is easily knocked off the stand. The stand diameter varies with age as follows:

Table 1. Variation in size of base with age

Age (months)	Base diameter (mm)	Notes
8	16	
10	14	
12	10	
15	6	
18	6	Narrow cylinder placed on stand

The setup is different from that usually encountered by infants at the relevant developmental stage, where grasping motions for similar sizes of object can be executed by taking a direct approach path. Here, the top approach is more successful since it confers less danger of knocking the ball off the support.

2.3 Experimental Results – Trial and Error and Observational Learning for Ball and Stand Paradigm

We can firstly examine whether the infants significantly improve their performance at the task by repeated trial and error. The following table shows the percentage of success on three sequential trials.

Only the infants at the age of 8 months improve their performance over repeated trials, other ages show no significant increase. For the 8 months olds, the critical increase comes between the first and second trials. Infants at age 15 months actually decrease in performance between the first and second trials, the reasons for this are not clear.

Table 2. Change in success at paradigm with repeated attempts, showing percentage of success on each trial

Age (months)	Trial 1	Trial 2	Trial 3
8	12.5	62.5	50
10	44.4	44.4	44.4
12	44.4	44.4	44.4
15	57.1	14.3	57.1
18	50	57.1	50

Table 3. Effects of observational learning on ball/stand paradigm

Age (months)	C Success (percentage)	E success	Significant
8	12.5	75	Y
10	44.4	55.56	N
12	44.4	50	N
15	57.1	70	N
18	50	66.7	N

Next, we can look at how the infants improve in their performance at the task after a single demonstration by an experimenter. The control group (C) is given the ball and stand with no demonstration, the experimental group (E) sees the demonstrator grasp the ball once, then attempts to grasp it themselves.

Considering the performance of the control group compared to the experimental group, we see that the 8 month old infants demonstrate considerable increase in success rate at the task after a single demonstration. Infants at all other ages show a performance increase after the demonstration, however the results are statistically significant only for the 8 month olds.

Given that the 8 month old infants demonstrate observational learning, we can consider what the infants are learning. Our hypothesis suggests that the infants are discovering non-perceived affordances and the ways in which to act upon them. This might manifest in two ways, one general the other more specific. The general discovery is that the ball is unstable, and so affords particular types of grip not immediately obvious (or rather, the obvious types of grip are likely to fail because of the ball's instability). The specific mechanism is the way in which the experimenter demonstrates grasping the ball (which involves a grasp from above).

2.4 Encoding of Affordance/Action Pairs

In the model, we encode the actions to be used on the affordance of grasping the ball as a direction of approach to the ball, moving to meet the contact points defined by the affordance. The contact points are assumed to be already learned as part of recognising the affordance. The angle of approach can either be vertical or horizontal. The simulation has an initial bias towards the horizontal angle of

approach. For both grasps, we assume that the infant already has the action as part of its motor repertoire, and can recognise it when used by the demonstrator (such that no new action is being learned). In the model, this translates to existing representations for the actions in the affordance/action pairs module, but low weights to the initially less preferred action.

We need to add a component of affordances (the contact points) into the action activity going to the motor planning module), although the contact point information would come from a separate affordance map in a more complex model, since this is not really a component of the action in its pure state.

2.5 Simulation Steps

The simulation of trial and error learning occurs with the following steps:

- 1) Present object. Object module activated.
- 2) The projection from the objects module to the affordances/actions module is used to stochastically select an affordant action from those known.
- 3) The affordance/action pair (contact points and a direction of approach) is combined with information about the current state of the system's arm/hand to form a motor plan
- 4) The motor plan is executed. During execution, sensorimotor feedback updates the current hand position
- 5) The plan is recognised to have succeeded (object grasped) or failed (object knocked over)
- 6) If the plan failed, reduce the weighting of the affordance used, if it succeeded, increase the weighting
- 7) Repeat

We measure the success rate for each trial. For the observational learning model, the steps are as follows:

- 1) Present object. Object module activated.
- 2) Teacher performs action on object. Affordance and action used are matched to existing affordance/action pairs
- 3) The weight of the object to the matched affordant action is increased
- 4) Object presented to simulated infant
- 5) Simulation proceeds as per trial and error task (results compared to that task)

2.6 Simulation Results – Trial and Error Learning

We firstly look at our results for trial and error learning, simulating the 8 month old infants improvement in performance by trial and error over a single trial.

We see in Figure 2 that the simulation shows a rapid gain in success rate after the first trial, from the trial and error learning.

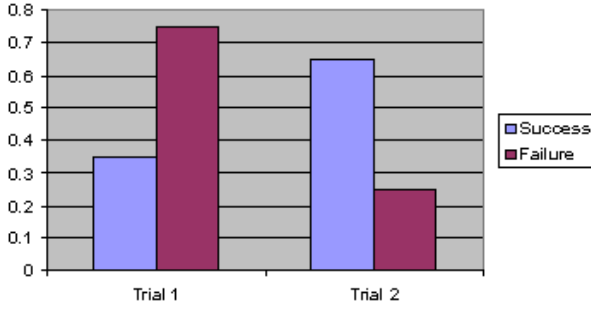


Fig. 2. Simulation results for the ball and stand paradigm showing improvement by trial and error between trials

2.7 Simulation Results – Observational Effects

Next we can look at the simulated observation learning, again for the 8 month old infants. Here we simulate a single demonstration of the task by a teacher using the grasp from above.

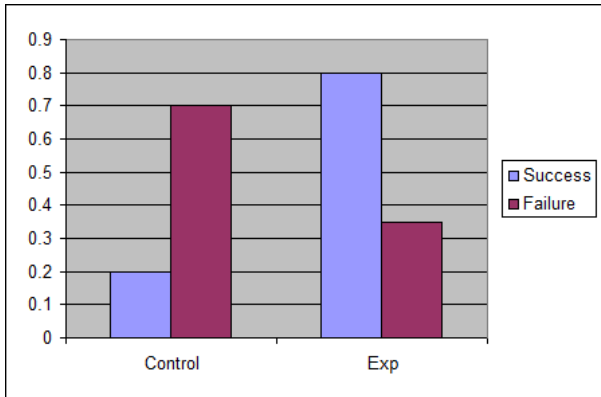


Fig. 3. Simulation results for the ball and stand paradigm showing improvement by observational effects

In this figure we can see that a single observation allows rapid increase in success percentage.

3 Methods

For the ball and stand paradigm we define an affordant action (for the affordance of grasping the ball) to consist of a set of three contact points, each defined in

physical space coordinates, and a variable specifying the angle of approach to the ball, which takes two possible values V (for a vertical approach) or H (for a horizontal approach). The object module is automatically activated with the ball object during the simulation trial. The projection to the affordance/action pairs module then activates one of the two possible affordant actions. Initially the probability of selecting the vertical approach angle action is p_V and that of selecting horizontal p_H .

Once an affordance is selected, a motor plan is produced to move the arm to the contact points involved via the approach specified in the affordance. We introduce fine motor control error, such that the fingers arrive at the location of the contact point plus a normally distributed (in three dimensions) error of magnitude E_{motor} and standard deviation σ_{motor} . For the horizontal angle of approach, any errors large enough to move the center of gravity of the ball over the edge of the stand causes it to fall off, failing the task. For the vertical angle of approach, the center of gravity of the ball must be moved more than twice the radius of the base away from its center for it to fall off (a simple way to model the lower chance of knocking the ball off the stand when the approach is from above).

If the ball is knocked off the stand, the probability of using that action on the affordance is adjusted downwards by T_{reduc} and the probability of using the other affordant action is increased correspondingly (such that the probability of using either remains 1). If the grasp is successful, the probability of using the affordant action selected is increased by T_{gain} and the other affordant action reduced correspondingly. During the observation section of the simulation, there is probability p_{recog} of the system correctly recognising the affordant action used. The probability of using this affordant action is then increased by T_{obs} , and the probability of the other affordant action decreased correspondingly.

3.1 Neuronal Basis

We describe here the mechanisms by which the model is implemented.

Dedicated representations - graded neurons. Areas where dedicated representations are needed use graded neurons, the activation of which represents whether that representation is active. These graded neurons have a membrane potential, V , following the equation:

$$C \frac{dV}{dT} = g_{leak}(V - V_{leak}) + I_{input} \quad (1)$$

and produce output:

$$O = \frac{1}{1 + \exp(-V/V_{scale})} \quad (2)$$

Goals are coded with two graded neurons - one for the goal “Get ball” and one for the goal “Push ball over”. These nodes are mutually interconnected with inhibitory connections, such that only one can be active concurrently.

Affordances are also coded with dedicated nodes, for "Grasp" and "Push". Affordant actions for the grasp affordance are coded with nodes for H and V, representing the horizontal and vertical grasps. Again, nodes have mutual inhibition such that only one can be active at a time.

The connections between affordances and actions are subject to plasticity, according to the equation:

$$w_{ij} = LV_iV_j \quad (3)$$

where w_{ij} is the weight between nodes i and j , L is a learning rate constant and V_i and V_j are the membrane potentials of neurons i and j . This connection can also be modified by the error monitor when a failed attempt to grasp the ball is detected.

Sensorimotor integration and motor planning. Both the sensorimotor integration and motor planning modules rely on vector subtraction. The motor planning module takes as input an action represented as a direction of approach to contact points of final finger positions and an approach vector, and the current position of the hand, and so performs the calculation:

$$Act = C - H \quad (4)$$

Where Act is the vector representing the action to be performed (as a trajectory of finger movements), H is the vector representing hand position, and C is the position of the contact points to be reached.

Mental simulation - goal inference. The mental simulation loop is used to extract the goal of an observed action on an affordance from the observed movements. It takes as input an encoding of the movements of the observed actor. This movement consists of a set of trajectory points, which are nine dimensional vectors. These are then used to, activate one of two goal nodes, the output of which is one of two possible goals, corresponding to those described above (get ball or push ball).

Actions. Actions are simply output as the positions of the end effectors of the system, resulting in triplet of three dimensional vectors.

3.2 Tube and Stick Paradigm

For the tube and stick paradigm, we use a simpler form of simulation. The system is presented with the setup, and then chooses a strategy to achieve the goal of retrieving the object from the tube. Initially the tube presents the affordance of trying to extract the object manually, A_{manual} . The stick provides the affordance of reaching into the tube A_{insert} , but there is only a probability $p_{A_{initial}}$ of this being recognised.

The system then chooses an affordance on which to act, either A_{manual} or A_{insert} . If the former is selected, the probability of success is p_{manual} , while if the latter is chosen, p_{insert} . The probability of success with the insertion affordance is much higher.

During observation, the demonstrator shows usage of the affordance A_{insert} which may then be perceived by the system.

4 Brain Basis

Development of the infant brain occurs in a topographic manner, from lower to higher areas: a hierarchy of visual areas is brought on stream or enabled to become active by axonal myelination in a successive manner. Such a process has been modelled, for example, in detailed neural network models of the hierarchical visual system $V1 \rightarrow V2 \rightarrow V3 \rightarrow V4 \rightarrow TEO \rightarrow TE$. Lower level synaptic connections were trained first in the model and the resulting outputs of the low-level feature detectors used to train the further higher-level feature detectors. In this way it proved possible to explain the sensitivity of V2 neurons to angles, of V4 neurons to partial edges of shapes, up to spatially invariant object representations in TE [3].

Such successive training of a hierarchy of modules, on top of the initial skeleton framework, arising from a genetic inheritance, also applies to prefrontal cortex starting with motor cortex and pre-motor cortices. Thus we expect that affordances, guiding the set of actions that can be taken on a given object, would also be developed in such a two-stage manner.

There are two sorts of affordances objects provide: those based on present experience and those learnt from past experience. The memorised affordances can be regarded as guiding possible actions that can be made, having been made in the past. The perceived affordances would then be those which arise through observation of trial-and-error processing or observational learning, also guided by the genetic skeleton. The perceived affordances would be stored in some short-term memory initially, but would, if salient enough, become part of the set of (long-term) memorised affordances.

We thus arrive at a picture of the learning of affordances as part of the overall learning of sensori-motor actions. The stored affordances module in figure 1 is to be regarded as the set of memorise affordances activated by the input of a given object code. It is this one-to-many mapping which is memorised by an infant in the process of babbling or making more goal oriented actions. The influence of goals coded in the goal module of figure 1 will begin to play their influence as goal creation occurs in the infant brain. Thus the stored affordance module would be part of long-term memory, very likely associated with developing object codes in the infant brain.

Results of brain imaging during observational learning and response indicate that considerable areas of the cortex are activated by observing an action being performed. In particular parietal and temporal areas are activated in this process, as well as those in pre-motor cortex; also STS is activated when an object is observed [4], corresponding to the possible significant points on the object by which action can be taken on it (such as the contact points).

Besides such features of an object there are also the relevant limb to be used and its orientation in making an action on the object (such as the horizontal versus vertical grip on the ball in the paradigm we have discussed). We expect

these to be encoded in pre-motor cortex (PMC) as part of the action plan, and in the parietal region as to the limb (associated with a body map)..

The model of figures 1 & 2 is thus related to possible brain sites as follows:

Vision: The hierarchy of visual cortical modules

Object recognition/object codes: The temporal lobe

Goals: Prefrontal cortices (especially DLPFC and VLPFC)

Error detection: Cingulate cortex (and possibly DLPFC)

Contact points of stored affordances: STS

Motor plans for acting on the contact points: PMC

Proprioceptive information: S1, S2

Part of body to be used: Parietal (such as PRR)

Sensorimotor integration: SPL, IPS (parietal reach area, etc)

Hand position: Posterior parietal, such as V6A

5 Discussion

We have shown that the simulation can reproduce experimental results showing improvement at the ball and stand task from both trial and error experimentation and observational learning. The observational learning improvement comes from allowing the transfer of the action on the affordance used.

5.1 Why Eight Months?

One of the most interesting questions posed by the experimental results is why the infants of 8 months of age demonstrate observational learning so clearly, while older infants do not (additionally the 8 month olds seem to learn by trial and error in a manner not shared by older infants). Part of this may be due to the unusually low success rate of 8 month infants attempting the task for the first time, which could be low due to the sample size. However the increase is certainly statistically significant. Another possibility is that the differences in task difficulty are such that strategy becomes more important than motor ability only for the 8 month olds, and that strategy is the key component of observational learning.

5.2 Learning Affordant Actions and Discovering Affordances

Another question we have already raised is that of how initial affordant actions are learned (and to some extent how affordances are discovered). Our model covers only the transfer of existing affordance/action pairs to new situations, not the learning of those affordant actions. This transfer assumes that the actions are already known to the infant, either in a different context or in the abstract form, however it is interesting to address how these actions are developed, and also how they might be modified during transfer.

Whether these actions can be learned by observation or require trial and error learning is unclear and yet to be determined. Since many actions are learned very early, this may be difficult to test. We can assume that there are some action primitives learned during early infant motor development. These are used to form basic actions such as finger movements. Experience and trial and error then allow these to form more complex actions, such as grasps. It may then be possible to develop these actions by observation.

For developing/associating the affordant actions we see in the experiment and simulation, we can consider a two stage process. In the first stage, the action is observed and roughly classified (type of grip, angle of approach, hand shaping). At this point, fine details such as the exact contact points of fingers must be inferred if they cannot be observed (possibly by mental simulation). In the second stage, trial and error allows the representation to be refined, such that contact points become more established, hand shaping is better, speed of approach becomes better tuned and so on. Further experiment is needed to determine whether this two stage mechanism is necessary, particularly looking at the second stage.

6 Conclusions

Based on the model results and other factors, we can draw some conclusions.

- That transfer/discovery of affordances and actions on those affordances can explain how observational learning can operate in this paradigm.
- That several other factors involving the infant's state and state of the object are important, and a more complex understanding of affordances is likely needed.
- That the demonstration of non-perceived affordances may be a more effective method of observational learning than the transfer of actions on affordances.

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