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What are you doing? How active and observational experience shape infants' action understanding

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From early in life, infants watch other people's actions. How do young infants come to make sense of actions they observe? Here, we review empirical findings on the development of action understanding in infancy. Based on this review, we argue that active action experience is crucial for infants' developing action understanding. When infants execute actions, they form associations between motor acts and the sensory consequences of these acts. When infants subsequently observe these actions in others, they can use their motor system to predict the outcome of the ongoing actions. Also, infants come to an understanding of others' actions through the repeated observation of actions and the effects associated with them. In their daily lives, infants have plenty of opportunities to form associations between observed events and learn about statistical regularities of others' behaviours. We argue that based on these two forms of experience—active action experience and observational experience—infants gradually develop more complex action understanding capabilities.

1. Introduction

> I hear and I forget. I see and I remember. I do and I understand.
>
> Chinese proverb

From the first days of life, infants observe their environment and the people acting in it. The human actions they watch form a continuous, intricate stream of complex information. How do infants perceive these actions and how do they eventually come to make sense of them? Which processes are crucial for their understanding of others?

In this article, we describe the processes that are thought to support action understanding in infancy. The paper starts with a discussion of methodological and theoretical issues concerning the study of action understanding in infants. Then, we review empirical findings on the early development of action understanding. Based on this review, we argue that active action experience is pivotal for infants' developing action understanding. Also, infants learn about others' actions through repeated observation, using their statistical learning abilities. To conclude, we propose that perceptual and motor experiences form the basis for more complex action understanding abilities, such as intention understanding, which develop later during childhood.

2. Studying action perception and action understanding in infants

Studying action understanding in infancy is not an easy endeavour. Traditionally, the great challenge of infancy research is to find measures that can tap into infants' cognitive processing. Different elegant research paradigms have been developed and used throughout the last decades to unravel the development of infants' action perception and prediction.

(a) Looking-time measures

For a long time, looking-time paradigms, such as the habituation or the violation of expectation paradigm, played a predominant role in studies on infants' action processing. In the frequently implemented 'Woodward-paradigm', for instance, infants are first repeatedly presented with an action, which is directed at one of two target objects (often a manual action, such as grasping) [1–3]. After habituation, it is investigated whether infants' attention recovers in response to a change in target object compared to a change in motion path. This suggests that infants selectively encoded the relationship between an agent and the target of an observed action [2] and is seen as an indication of goal attribution by the infant. Also, looking-time paradigms have been used to examine infants' sensitivity to the efficiency of others' actions (e.g. [4–6]) as well as early mind-reading abilities (e.g. [7,8]).

Such studies implementing looking time as a measure of a novelty response have been immensely important for the field, as they provided the opportunity to systematically explore how infants perceive and process others' actions. These studies are, for instance, informative about which aspects of an observed action infants preferably attend to. On a more general note, however, the suitability of habituation-based looking-time methods to study complex cognitive mechanisms in infants has been questioned, as fully controlling for perceptual differences between conditions and excluding low-level alternative interpretations can be extremely difficult [9,10].

(b) Anticipatory looking measures

Recently, many studies started using anticipatory eye movements during action observation as an indicator of infants' action prediction [11–15]. It has been shown that when watching actions, infants—like adults [16]—perform anticipatory eye movements thereby predicting the course of the observed action [17,18]. Measuring visual anticipations thus allows assessing, for instance, which object infants expect a person to grasp or act on [11,19], which path they expect a locomoting agent to take [20,21] or whom of two interaction partners they predict to act next [22].

Compared to habituation-based looking-time methods, the measure of predictive gaze has several advantages [12]. It does not require a habituation or learning phase and thus assesses infants' online predictions. In principle, it can also be employed with older children or adults, which allows comparisons over different populations. But most importantly, anticipatory looks are a direct measure of the observer's expectations, whereas habituation-based looking-time measures can only assess whether infants are sensitive to changes of a certain aspect of a previously observed action. However, it is important to note that this paradigm provides information about which target location or target object infants expect an action to be directed at, but does not allow any conclusions about whether infants identified the higher order goal of the observed action (cf. [12]): if an infant predicts that a person will bring a cup she has grasped to her mouth rather than to another target location, this does not necessarily imply that the infant has identified the observed action as serving drinking.

(c) Other behavioural measures

Another elegant way of assessing infants' perception and understanding of others' actions is the use of infants' overt behaviour during interactive situations. Behne and colleagues, for instance, studied infants' responses to an experimenter who was either unwilling or unable to pass infants a toy they wanted. This allowed them to test whether infants show differential reactions to behaviour expressing different intentions [23]. Other studies used imitation tasks to examine infants' perception of an observed action. Infants as young as nine months readily imitate actions they watch others perform [24], and the way a young child reproduces an observed action can be informative about how the child perceived and interpreted what she saw [25–27].

(d) Neuroscientific methods

Finally, the processes involved in action observation have been directly studied at the brain level and different neuroscientific techniques have been used to do so. Mostly, neural markers that have been well established in adult research are implemented to investigate how infants process actions they observe [28–30]. Based on the idea that during action observation, an internal motor representation of that same behaviour within the observer is activated [31,32], many studies have focused on measuring activation of the infant's motor system during action observation. In human electroencephalography (EEG), spectral power in the μ and β frequency band over the motor cortex decreases with movement, intent to move or during the observation of others' actions [33,34]. Therefore, μ and β wave suppression are frequently used as indices of motor activation during action observation also in infants (see for reviews, [35,36]). As EEG has a poor spatial resolution, recent studies have also made use of functional near-infrared spectroscopy (fNIRS) to study which brain areas are activated when infants process others' actions [37–40]. Carefully designed neuroimaging studies bear a great potential of further unravelling the mechanisms of action processing in infancy.

A general challenge of infancy research and thus also the study of action perception and understanding in infants is that we can never be entirely sure how an infant perceived the experimental situation and must rely on our interpretation of the infant's responses. Although the issue of a possible over-interpretation of findings on infants' cognitive processes has mainly been discussed in the context of looking-time paradigms (e.g. [9,41–43]), it applies to all methods that employ indirect evidence to get at infants' cognitive abilities. It is thus important to keep an open mind for lower level mechanisms that may account for findings that at first glance seem to imply high-level cognitive operations, such as intention attribution, in infants. Moreover, seeking converging evidence across different methods and from different laboratories might also be of crucial importance.

Putting together evidence from different theoretical approaches and research paradigms, we see that our understanding of infants' action perception and understanding has increased tremendously over the last decennia. We now turn to reviewing empirical findings on how infants' action understanding develops and which mechanisms are crucial for the emergence of action understanding in infancy.

3. The role of active action experience for action understanding

A number of theoretical approaches emphasize the importance of one's own action experience for action comprehension

[44,45] and stress the close link between action experience and action understanding early in infancy [46].

(a) Action experience and action understanding in adults

When adults observe other people performing actions, they readily process and interpret what they see in terms of hierarchically organized action goals (e.g. [47]). According to ideomotor theories [31,48,49], observing someone else perform an action activates an internal motor representation of that same behaviour within the observer. This activation of the observer's own action system is thought to support action decoding and understanding (e.g. [50–52]). Initial accounts assumed a 'direct matching' between observed actions and the activation in the motor cortex and proposed that action understanding occurs as a result of an automatic mapping [52,53].

However, action understanding occurring solely from the immediate sensory input of the observed action is possible only in rare cases of simple, unambiguous actions. If we were to observe a person reaching for a scalpel, how would we be able to tell whether the person is going to perform a lifesaving operation on a patient or whether he is going to kill the person lying helplessly in front of him? This discrimination cannot be made solely based on the observation of the grasping action itself, but only when taking into account contextual information, for instance whether the action we observe is situated in an operation room or not (Dr Jekyll and Mr Hyde example from [54]). Some recent theories thus propose that action prediction and action understanding occur from a combination of motor simulation and information coming from the context of the observed action and our knowledge about the world [55–57].

The discovery of so-called mirror neurons in the ventral premotor cortex of the macaque monkey in the early 1990s provided neurophysiological support for theories that emphasize the role of motor simulations in action understanding and imitation. This set of premotor neurons has been shown to respond when monkeys perform an action as well as when they sit motionless observing someone else performing this action [58]. A similar action observation–execution matching system has been proposed to exist in the human brain and is thought to involve the ventral premotor cortex and the inferior frontal gyrus [52,59], as well as the primary motor cortex [60].

In adults, the extent of mirror activation during action observation is dependent on the observer's experience of physically performing this action [61–63]. If an action that is outside of the human repertoire is observed (such as barking), there is typically little activation found in the premotor areas [64]. Expert dancers who watch another person dancing show stronger motor activation than control subjects who are trained in another dance style. For acquired motor skills, motor activation thus is modulated by the observer's level of proficiency and motor familiarity with that skill [65], whereas solely visual familiarity with the action acquired through observation seems to have far less impact [66].

Probably owing to enhanced simulation of the observed kinematic acts ([67–70]; cf. [71]), observers are better at predicting the outcome of actions [72] and at estimating the duration [73] of motorically familiar actions when they watch them performed by others. Moreover, experienced adults tend to outperform novices when asked to recognize, categorize and recall observed actions [74–77]. Also, motor experience can have a direct impact on visual action recognition without being mediated by visual experience. If adult participants are trained on a novel coordinated body movement while being blindfolded, they improve in their visual recognition of this movement without having received any visual feedback about this new action [74]. The adult literature thus provides us with broad evidence that motor expertise fundamentally changes how humans perceive and process actions they observe in others, which leads to the question of whether motor experience is as powerful at changing action perception and augmenting action understanding early in life.

(b) Action experience and action understanding in infants

Already Jean Piaget [78] put forth the idea that action experience is fundamental to cognitive development. Beyond a general effect of action on cognition [79–81], infants' experience in carrying out specific actions contributes to their understanding of these same actions in others. Several theoretical accounts stress that action production and understanding are deeply intertwined from early infancy and that this relation drives the early development of social understanding (e.g. [82,83]). It has even been suggested that we can only perceive and understand in others what we can do ourselves [45].

In line with these theoretical accounts, we propose that action experience is an important process through which infants develop the capacity of action understanding. Their active experiences provide infants with rich, multifaceted representations of actions and the corresponding action effects (cf. [84,85]). Through repeated execution of actions, infants form associations between these motor acts and their sensory consequences [86]. When infants subsequently observe these actions in others, they can use their motor system to predict the outcome of the ongoing actions.

A broad body of studies on the relationship between infants' action experience and action perception are in support of this view. First of all, studies employing a broad range of methods (such as EEG, fNIRS or electromyographic recordings) have shown that when infants observe others' actions, their neural motor system becomes activated [87–90,28,39]. However, how exactly the mirror system develops in infancy and early childhood is still a matter of debate [91]. Whereas some researchers suggest that humans are equipped with an innate matching system, at least in a rudimentary form [92,93], others propose that the mirror properties of the human brain develop as a result of sensorimotor learning [57,94,95]. Both notions, however, acknowledge that the mirror system is modulated by sensorimotor learning throughout the course of development.

In line with this and in analogy to adult findings on the effects of motor expertise, motor activation during action observation has been found to be influenced by the infant's motor skills [96]. Infants who were proficient crawlers showed a stronger activation of their motor system when watching other infants crawling compared with walking, and this effect appeared to be directly related to the duration of their crawling experience, even when controlling for maturational age. Moreover, in another recent study, we showed that eight-month-old infants who had been trained to shake a novel rattle to produce a specific sound effect for a week responded with motor activation to the rattle sound during a subsequent test session. This suggests that young infants readily acquire new sensorimotor associations and speaks to the flexibility of the developing mirror system [86].

But what is the evidence that active action experience indeed enhances infants' action processing and understanding? Several studies now suggest that in adults, motor activation during action observation is causally related to generating predictions about the course of the observed actions [68–70]. These studies have used a motor interference task [68] or transcranial magnetic stimulation of the motor cortex [69,70] to show that motor system activity is necessary to perform anticipatory eye movements to the target of an ongoing observed action. In addition, there is strong evidence that infants' motor experience is closely linked to their action prediction [97–99]. It has been demonstrated that infants' ability to anticipate the target object of an observed grasping action is synchronized with the onset of their performance of these actions [97,98]. In accordance with these findings, we showed in a recent study that infants who were proficient crawlers but inexperienced walkers were more accurate in visually predicting the timing of other infants' crawling compared with walking. Toddlers and adults who were experienced in both, walking and crawling, performed equally well for both observed actions [99].

More generally, many studies have shown that infants process actions differently if they have active experience with them [100–104]. When infants of 10 months of age, for instance, observe a means-end action within the 'Woodward-paradigm', they respond selectively to a change in target object only if they are capable of carrying out means-end actions themselves [105]. In another study, infants as young as three months of age were given the opportunity to gain action experience with successful goal achievement: infants were equipped with sticky mittens, which enabled them to 'grasp' a toy, which they otherwise would not have been able to do. Afterwards, they watched another person grasping similar toys. The infants who had been provided with additional action experience were more sensitive to a switch in the target objects of the grasping actions than infants who had not experienced 'grasping' themselves [106].

Training studies, in which infants receive active experience performing novel actions, are especially important in this context, as they allow examining causal effects of action experience. Using this approach, it has been shown that receiving experience with novel actions changes how infants process these actions when they perceive them performed by others and that such effects are evident in their looking behaviour [100,101,104,106] as well as in the response of their neural motor system [86]. More of such training studies are needed to better understand how infants' action perception and understanding are facilitated by active experience.

In summary, a broad body of literature now demonstrates that action experience changes how infants perceive others' actions. Specifically, it has been shown that the motor system of the brain processes actions differently depending on whether they are in the infant's motor repertoire or not. Recent adult research has provided evidence that the motor system is causally involved in making predictions about observed actions, and, in line with this, infants have been shown to be better at predicting the course of an ongoing action, which is motorically familiar to them. In summary, there is now strong support for the notion that infants' action experience plays a fundamental role in their developing action understanding.

4. The role of observational experience for action understanding

Of course, active action experience is not the only road to and sole prerequisite for action understanding. As adults, we are able to understand that a bird is flying from the ground onto a tree, although we have no experience with this specific action ourselves. However, we have observed many birds fly in our lives and have learned from these observations. Likewise, infants are also able to pick up information about actions long before they can carry these actions out themselves, as they show vivid interest in others' actions from early in life. By six months of age, for instance, infants have acquired some knowledge about everyday objects and how these are typically handled [12,14,29,107]. Without having actively experienced the observed actions and thus solely based on their observational experience, six-month-old infants show predictive looks to the mouth when they see a person grasp a cup and to the ear when they see her pick up a phone [12].

How does observational experience enhance infants' action processing and understanding? How do infants come to predict how an action will unfold without having ever performed it themselves? One route of observational learning may be through associative and statistical learning. From birth onwards, human infants are able to quickly form associations between events (e.g. [108]). Moreover, young infants have been shown to aggregate information over multiple occurrences and extract statistical patterns from repeated observations [109]. Infants' impressive statistical learning abilities have been demonstrated to be present from a very young age on and across different domains [109]. By eight months of age, by example, infants can use the statistical structure in a continuous stream of syllables to extract which syllables co-occur and thus tend to form words [110]. They also detect statistical regularities in sequences of tones and visual stimuli [109,111,112]. By about 1 year of age, infants quickly associate new words and objects [113], even if they have to aggregate information over multiple and individually ambiguous scenes [114]. On the basis of this evidence, statistical learning has been suggested to play a crucial role in early cognitive and social-cognitive development [109,115].

In the action domain, infants have plenty of opportunities to form associations between observed events and learn about statistical regularities of others' behaviours. From early on, their attention is drawn to human motion [116] and to other people's faces and hands [117]. This provides infants with crucial information about others' actions, but also their gaze, emotional expressions and information about objects and how they are manipulated. Moreover, infants learn about the statistical regularities within the seemingly endless, complicated stream of actions they observe in others, and towards the end of the first year of life infants can parse a series of actions they observe into segments of meaningful sub-actions [118]. They begin to attend especially to the effects of actions they observe [119] and expect a person to reach for the same target object again after they have observed her grasping it before [11,120]. When observing an agent repeatedly move along one of two paths, infants as young as nine months of age quickly learn to anticipate which path it will take, and the frequency information stemming from previous observations seems to be the strongest factor guiding infants' action predictions [21].

Forming associations between events (such as between an everyday object like a cup and the location where it is normally brought, the mouth) and extracting regularities from a series of observations thus probably helps infants to predict how actions will unfold which they cannot yet simulate in their motor system. In a recent study, we showed that when learning about others' actions through observation, infants might not only form associations between visual events, but also between different modalities, as they were able to link the percept of a novel action effect to their motor system through mere action observation [121]. Infants of nine months of age observed their parents shaking a novel rattle and bringing about a distinct sound effect during several training sessions within one week. When subsequently listening to the rattle's sound effect, they showed an increased motor activation. Without ever having shaken the novel rattle themselves, just through observing their parents' actions, infants had formed an association between the sound effect and the action representation in their own motor system. This illustrates that perceptual action experience can include more than just the visual domain. When infants were observing their parents handling the rattle, the representation of the corresponding action in their own motor system was probably activated and associated with the novel sound effect (cf. [122] for an equivalent finding with adults). This acquisition of novel action-effect associations might form the basis for infants' unique social learning abilities.

Observing others' actions thus is an important route to action understanding in infancy. Only a few studies, however, have aimed to answer the intriguing question which of the two types of experience, active or observational, has more impact on infants' action processing. From these studies, it appears that active action experience is especially powerful and has a unique effect on infants' action processing early in development [101,123], at least in the case of short-term, within-experiment effects. However, whereas a brief period of active action experience seems to be sufficient to change infants' processing of the exact same action [106,123], for action processing to fundamentally change and generalization over different situations to take place, more active action experience seems to be necessary [15,96,101,123]. Yet, it remains difficult to directly compare the impact of both processes because experimentally matching active and observational experience is challenging. In the daily life of an infant, of course, active and observational action experience occurs intermixed and closely connected. Whereas younger infants with limited motor abilities might rely more on their observation of others' actions, with motor development progressing, active experience probably gains importance (cf. [12]). In the end, action understanding might emerge from a complex interaction of both processes, and examining how exactly these processes interact to bring about action understanding is an exciting research direction (cf. [124]).

5. The principle of rational action

Aside from self-produced actions and observational action experience, there are other mechanisms infants have been suggested to rely on to understand actions they observe. For instance, infants might apply a rational principle to actions they observe and have expectations about the efficient means an agent will choose to achieve a goal (e.g. [26,125]). Infants are thought to also use this rational principle to understand actions they observe. By assessing what end state would be efficiently brought about by an action and at the same time taking into account the particular situational constraints, infants might be able to infer the likely goal of the observed action [126,127].

When presented with a non-human agent (i.e. a ball) approaching a goal by a detour path, such as jumping over an obstacle, infants of six to nine months of age have indeed been shown to look longer when the agent still used the detour rather than a direct path after the obstacle was removed [4–6]. However, new empirical studies have demonstrated possible alternative explanations to paradigms that were thought to measure infants' rational analysis of an observed action [21,128–131]. It has, for instance, been suggested that infants' longer looking to an agent taking a detour rather than a direct path might not be caused by their surprise about the inefficient action, but might be a response to an event, which is inconsistent with their long-term experience with objects and agents in the environment. In daily life, infants hardly ever observe that humans and other agents perform sudden jumps during their movements, and balls tend to move linearly across surfaces without making swerves. In accordance with this alternative explanation, a recent study from our own laboratory found evidence that in a paradigm in which an agent could choose between an efficient and an inefficient path, it was only frequency information about previous actions that determined infants' action predictions [21].

More evidence for infants' use of a rational principle when processing others' actions originally came from the rational imitation paradigm. In the rational imitation paradigm, it is examined whether infants take into account observed situational constraints when imitating [26]. After having observed a model whose hands are constrained act on a light switch with her head, infants tend to imitate the action using their hands and thus appear to take into account the situational constraints of the model, which do not apply to themselves. The authors thus suggested that imitative behaviour reflects cognitive processes, such as an evaluation of the observed action in terms of efficiency. Several recent studies have challenged these findings by demonstrating that imitation behaviour, which appeared to be guided by the child's reasoning about the observed situation, might have been caused by lower level perceptual and motor processes [128–131]. As the discussion is still ongoing [132,133], it is currently unclear whether infants already make use of a rational principle to understand others' actions.

But how might infants develop an expectation that other agents choose efficient means? One possibility is that infants need active experience before their perception of others' actions is influenced by the efficiency principle [134,135]. From adult research, we know that our perception of a situation is strongly dependent on our action capabilities. The same distance, for example, looks farther to an elderly than to a young person, and a hill is judged to be steeper by individuals who are out-of-shape compared with fit subjects [136,137]. In the same vein, infants might need active experience with locomoting and the effort it takes to move along short and long paths in order to learn about efficiency and develop expectations about other agents' efficient means. Additionally, infants might learn through repeated observation that agents in their environment tend to prefer the shortest routes, direct grasps or least effortful means across different situations (cf. [21]). More research is needed to clarify how perceptual and motor experience influence the development of efficiency expectations.

6. From behaviour reading to mind reading

So far, we have discussed how infants become able to predict and understand actions they observe. Mature action understanding, however, exceeds this kind of action understanding, because as adults we not only have the ability to predict how an observed action might unfold, but also to attribute an intention to the action. As illustrated in the example of Dr Jekyll and Mr Hyde mentioned before [54], the extraction of an intention from an action is not trivial, as different intentions—here, to cure or harm—can underlie the same specific action. But how do infants progress from reading others' behaviours to understanding others' minds?

It has been suggested that infants possess the ability to understand others' intentions from early on and that their action understanding might thus already go beyond what is directly observable in an action. For example, infants' performance in the Woodward-paradigm has been interpreted by some as an indication that six-month-olds did not only learn about the relationship between an actor and the target object of her grasping actions, but are also able to understand that it is her intention to grasp this object. Moreover, in an interaction study, nine-month-old infants have been reported to respond differently to an experimenter who was either unwilling to give them a toy or tried but failed [23]. Also, it has been shown that when observing an adult model trying but failing to perform an action on a novel tool (such as trying to pull apart two parts of a dumbbell), infants of 18 months imitate the action as it might have been intended, although they never actually observed the model carry it out successfully [27].

However, several recent papers have rightly reminded us that we must be careful to not over-interpret infants' behaviour, which at first sight might appear to be evidence for infants' intention understanding. They provided alternative, lower level interpretations of these and other findings, which used to bolster claims of advanced action understanding abilities in infants (e.g. [115,138–140]). In this context, it has, for example, been argued that infants' imitation of unobserved end states does not necessarily imply that they understood the intentions of the model who tried but failed to perform a certain action. Their imitation performance might simply be the result of them copying the model's trying behaviour, which inevitably led to the 'intended' result [115]. Also the fact that infants respond differentially to an experimenter who is either unwilling to give them a toy or tried but failed to pass it to them does not prove that infants correctly identified these different intentions. However, it might just be a consequence of the fact that the adult's behaviours are indicative of different probabilities of them eventually getting the toy [115]. It thus remains an open question whether infants understand others' intentions from early in life onwards.

Alternatively, young children might gradually develop from being able to read others' behaviours to understanding others' minds on the basis of their experiences with own and others' actions. As the Dr Jekyll and Mr Hyde example shows, intention understanding exceeds a one-to-one mapping between an observed action and an intention. In many cases, therefore, an integration of contextual information is necessary, such as information about the situation in which the actions take place or the emotional expression on the actors' faces [55–57]. Throughout the months and years of early childhood, infants have ample opportunity to collect probabilistic knowledge about others and their actions as well as the different situations in which they occur. Their steadily growing knowledge influences their perception of others' actions and might further shape their action understanding (cf. [141]). In line with this, it has been proposed that young children gradually come to understand unobservable action goals through the experience of their own actions and mental states as well as their impressive statistical learning skills that allow them to see patterns in observed and experienced behaviours [115]. A failure to acquire such contextual knowledge necessary to modulate the direct perception of actions and understand non-observable action goals might even be at the core of developmental disorders like autism (cf. [142,143]).

7. Conclusion

In this article, we have outlined how infants come to understand actions they observe in others on the basis of their perceptual and motor experiences. When infants are still young, they might primarily learn about others' actions through observation. Using their powerful associative and statistical learning abilities, infants can pick up on regularities in others' actions and on which actions are followed by which action effects. As their motor development progresses, infants' active action experience becomes an essential source of their developing action understanding. On the basis of these general mechanisms, young children might gradually develop also more complex action understanding abilities, which allow them to progress from being able to read others' behaviours to understanding others' minds.

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