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ARTICLE

Child Development Perspectives

Infants' predictive minds: The role of motor experience

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Abstract
The ability to predict upcoming events is essential in infancy because it enables babies to process information optimally and have successful goal-directed interactions with their environment. In this article, we examine how infants generate predictions in perception, cognition, and action, and address whether and how their predictions are motivated and affected by their motor development. Our synthesis of research demonstrates that infants form predictions in the perception, cognition, and action domains based on perceived statistical information, pre-existing and newly generated knowledge, and internal motor models. Our analysis reveals that infants' increasing fine and gross motor experiences have a moderating impact on the elaboration of the different bases for predictions. Based on this, we conclude that new motor experiences enable infants to constantly improve the bases from which they generate and update their predictions.

KEYWORDS
infants, motor development, prediction

From the beginning of life, infants' perception, cognition, and action show emerging signs of predictive processing (Köster et al., 2020). A predictive stance allows for optimal gathering of environmental information from the flow of information that constantly surrounds an infant, which enables and facilitates successful goal-directed interactions with their environment. In adults, the ability to generate predictions has been elaborated by predictive coding theory (Rao & Ballard, 1999), which proposes that the brain constantly generates and corrects predictions to perceive and act efficiently on the world. The theory also proposes that perception, cognition, and action all follow a predictive logic in pursuit of the goal of reducing sensory prediction error by changing internal states (perceptual inference) or acting on the world to change sensory input (active inference; Clark, 2013; Friston, 2010). In this article, we discuss how infants generate predictions in perception, cognition, and action, and how infants' predictions are motivated and affected by their motor development.

INFANTS' PREDICTIONS IN PERCEPTION, COGNITION, AND ACTION

Perception

Perception involves recognizing the structure of a dynamic, multimodal environment. From birth, infants have the astonishing ability to detect regularities, so-called *statistical information*, in stimulus sequences by processing specific distributions of frequencies, redundancies, or transitional probabilities of stimuli in a sequence (for an overview, see Johnson, 2020; Saffran & Kirkham, 2018). They can perceive such regular information in their environment without any instructions or feedback. In seminal work by Saffran et al. (1996), 8-month-olds segmented words from fluent speech based solely on the statistical relations between neighboring speech sounds, and they responded significantly to violations of these relations. In subsequent research, infants recognized statistical information not only in language but also in sequences of visual stimuli, such as arrangements of objects (Kirkham et al., 2007) or observed actions (Monroy et al., 2017). Thus, infants' ability to detect statistical patterns can be considered an early basis for their predictions in perception. As assumed for adults, correct predictions allow efficient processing of incoming stimuli, while violations elicit a prediction error whose minimization leads to a continuous improvement of the predictions (Rao & Ballard, 1999). In the aforementioned studies with infants, researchers determined infants' predictions from the fact that they responded to a violation of the presented statistical patterns—for example, with longer looking times. (For the sociodemographic characteristics of the studies reviewed herein, see Table S1.)

Researchers have also demonstrated how infants seek to reduce the prediction error via various perceptual inferences. In one study (Romberg & Saffran, 2013), infants saw a brief video repeatedly on the left side of a screen and looked predictively to the left. After several trials, the video ran on the right side, but infants did not change their internal status and continued to look to the left. However, after a second unexpected trial, they reduced the prediction error by changing their internal status and predicted sensory stimulation from the right. This suggests that infants reduced the prediction error via perceptual inferences based on the probability they had observed, but not based on a single counter-example. Recurrent neural networks are optimal at memorizing such previous information in sequential stimuli. In seminal computational work, Elman (1990) was the first to implement a so-called *hidden layer* enabling a neuronal network to effectively capture long-term dependencies in sequential patterns. Thus, infants' ability to recognize and learn the statistics of their perceptual inputs enables them to make corresponding predictions, which they constantly and increasingly correctly update.

Cognition

Cognition in infancy mainly comprises so-called *core knowledge* about objects, numerical quantities, spatial relations, and social entities that require little or no prior experience (Spelke & Kinzler, 2007). Across many studies, infants responded with a predictive reaction and reliably looked longer when they watched events that defied the expectations an adult would generate—for example, when an object hidden in one location was revealed in a different location (Wilcox et al., 1996). Thus, infants used their core knowledge as the basis for their predictions and responded with surprise when it was violated. In one study, 6- to 9-month-olds' visual responses to violations of their numerical core knowledge were reflected in relatively early EEG responses (300–400 ms; Berger et al., 2006). However, in a separate study, 12-month-olds responded to a prediction violation with relatively late neural responses (700–1000 ms; Kouider et al., 2015). In this study, infants did not respond to a violation of core knowledge but to a violation of the prior learning of an arbitrary mapping between a sound and an object category (flower, face).

This comparison regarding the type of knowledge base that elicited a prediction in terms of a surprise response is interesting because it suggests that various neural dynamics are involved, depending on whether an infant's basis for prediction requires almost no learning and involves within-domain computations (i.e., core knowledge) or depends on newly perceived and learned associations involving cross-domain computations. A third study added another factor to this comparison, arguing that in such work, infants are confronted with different types of violated events (Stahl & Feigenson, 2019). When core knowledge is violated, infants would generate a prediction due to impossible events, while when newly learned associations are violated, they would predict based on improbable events. In this work, researchers hypothesized that violations of impossible events would produce a stronger interest in subsequent learning than would violations of improbable events.

In fact, in an earlier study, infants who experienced a violation of an impossible event produced active inferences by systematically exploring the object involved with their hands (Stahl & Feigenson, 2015); they did not do so with the object involved in the possible event. To understand more thoroughly infants' drivers for learning, researchers should systematically uncover how infants reduce the prediction error after experiencing impossible and improbable events. Other studies have convincingly demonstrated that infants' predictions are also associated with their later cognitive processing (e.g., Gottwald et al., 2016; Marciszko et al., 2020). The authors of these studies provided evidence for a strong association between infants' predictions and their executive functions in the following years. Thus, infants' innate and newly emerging knowledge serves as a base from which they form and steadily update their predictions, which also affect their later cognitive processes.

Action

Actions include any kind of goal-directed movements. Infants must learn to perform and understand goal-directed actions so they can interact with the environment successfully. Predictions are always inherently involved in actions because they allow individuals to overcome the temporal delay of perceptual and action processes. They are also involved in the sense that actions can reduce the potential discrepancy between expectations and incoming sensory data to change sensory data. Inspired by Piaget (1952), researchers have assumed that the sensorimotor system mainly represents the fundamental basis for the formation of goal-directed actions. This assumption is also found in research by Nagai (2019), who proposed two modules of infant predictive actions. At the first, the sensorimotor system executes actions and records the resulting sensory feedback from the environment. In the second, the predictor includes the internal model of the sensorimotor system. The aim of the predictor is to accurately simulate the sensorimotor system by learning to minimize the predictive error, calculated as the difference between the actual sensory feedback and the predicted one.

Nagai assumed that infants' internal models constantly improve with increasing sensorimotor experience. Especially for basic manual actions, like grasping an object in reaching distance, infants seem to base their predictions on an internal model that is aligned to the visual information for the goal in the environment. This can be seen in research indicating that infants show developmental improvements in pre-shaping their hand and optimizing their reach trajectory to grasp objects varying in size and orientation (e.g., Ransburg et al., 2017).

Infants appear to steadily improve their predictive grasping actions via active inferences, thereby generating a so-called *forward model* of their grasping. Such models predict the sensory consequences of actions on the basis of efferent (i.e., outgoing, from the central nervous system to the periphery) action commands (Miall & Wolpert, 1996). Memorizing the mapping of movements to their effects is thought to generate such internal models (Rao et al., 2007). In one study, from around 6 months, infants relied on such forward models to predict the actions of other people (Gredebäck et al., 2018). With age, they increasingly adjusted the models to the difficulty of the upcoming action characteristics (Gottwald et al., 2017). Thus, infants refine the ability to perform goal-directed actions in the first year of life as their capacity to generate internal forward motor models of their own actions improves with age. As a consequence, they become increasingly precise in predicting the outcomes of their own and others' actions.

Overall, we can conclude that infants form predictions based on perceived statistical information, innate and acquired knowledge, and their internal motor models, which they improve steadily by reducing the prediction error via perceptual and active inferences. We can assume that these bases for forming predictions work both separately and in interaction with each other, depending on the situational requirements. Infants' impressive predictive abilities raise the question of what source motivates and drives the emergence of these abilities. Based on Nagai's assumptions (2019) and predictive coding theory, we can assume that there is a kind of intrinsic motivation to minimize the prediction error, which leads to increasingly correct predictions; this would imply that the early predictive processing system constantly drives itself to make predictions.

The first evidence that the infant's brain seems to generate predictions in such an autonomous manner around 6 months was provided by Emberson et al. (2015). After learning visual–auditory associations, when the visual information was unexpectedly omitted and only the auditory component of the association was presented, infants showed activation in the occipital cortex, as if the visual stimulus had actually been presented. This was not the case when an omission was expected to happen. This suggests that infants' brains generate predictions solely based on prior information and that sensory activity is modulated by the violations of these predictions.

However, even if the predictive processing system itself ensures constant adaptation of predictions, what feeds this autonomous process of generating predictions? One possible influence might originate in infants' increasing motor experiences, which might lead steadily to changes in infants' bases for forming corresponding perceptual, cognitive, and motor predictions, which are modulated by learning to minimize the prediction error. Since the seminal works of Piaget (1952) and Gibson (1988), researchers in developmental psychology have identified significant evidence demonstrating that infants' improvements in perceptual-cognitive abilities are linked to achievements in motor development (Campos et al., 2000). Therefore, we assume that infants' motor experiences trigger and enhance their predictive abilities in various domains.

LINKS BETWEEN INFANTS' PREDICTIONS AND MOTOR DEVELOPMENT

Predictions based on perceived statistics and motor experience

Infants' own changing motor achievements open and close gates, selecting from the environment different data sets to enter the internal system for learning the statistics of their environment, on the basis of which infants form their predictions (Smith et al., 2018). A study that provides direct evidence of this link tested whether infants' own fine motor proficiency was linked to their statistical learning skills to predict upcoming sequential actions (Monroy et al., 2017). Eight- to 11-month-olds with own dominant pincer grasp showed an earlier increase in correct predictions for pincer grasp regular actions as opposed to whole-hand and random actions, while infants with own dominant whole-hand grasp showed the contrary pattern. This suggests that infants' ability to perceive statistical regularities and draw correct perceptual inferences is facilitated when the observed action matches their own motor abilities.

In three related studies, infants' perception of the statistical regularity of visuospatial object behavior, which was not related to a person's action, was also enhanced by their motor experiences. In the prediction task of these studies, a three-dimensional object rotated back and forth and made target objects visible on the left or right or above or below. Researchers analyzed infants' looking at the target locations before the objects were visible. In one study (Gehb et al., 2022), 6-month-olds were tested before and after having been provided with three specific motor experiences: (1) In the passive condition, infants were moved through a movement track equipped with various objects; (2) in the active condition, infants learned to move with a baby walker through the track; (3) other infants belonged to a waiting control group. Only the passively moved infants had higher prediction rates in the post-training prediction tests than in the pre-training tests. The visual tracking of objects while being pushed through the track seems to have facilitated infants' perception of and ongoing perceptual inferences about the statistics of occlusion and the reappearance of the target objects in the prediction task.

In another study (Kubicek et al., 2017a), 7- to 8-month-olds were tested with the same prediction task and with a manual object exploration task. Infants with a high level of spontaneous object exploration skill had higher prediction rates than infants with less proficient object exploration skills. In the third study (Kubicek et al., 2017b), 9-month-old crawling and noncrawling infants were tested with the same task. Crawlers had higher prediction rates during test trials than noncrawlers. Thus, empirical evidence supports our assumption that motor experiences enhance infants' perception of statistical information, enabling them to infer correct predictions via steadily improving perceptual inferences.

Predictions based on knowledge and motor experience

The idea that infants' emerging knowledge serves as a basis for their predictions and is related to motor experiences can be traced to Piaget's theory (1952), especially to his concepts of *accommodation* and *equilibrium*. Accomodation is the process that occurs when new information conflicts with existing schemas and causes a child to modify the existing cognitive schemas. Cognitive equilibrium is a state of balance between the child's mental schemata and their experiences with the environment. Such balance occurs when children's expectations, based on prior knowledge, fit with new knowledge. Piaget conceived *equilibration* as an ongoing process that refines and transforms mental structures, constituting the basis of cognitive development. Equilibration also explains a child's motivation for development: They naturally seek equilibrium because disequilibrium, the mismatch between one's way of thinking and one's environment, is inherently dissatisfying. When children encounter new discrepant information, they enter into a state of disequilibrium. Children can return to a state of equilibrium via accommodation.

In terms of the main driver of change, the concepts of accommodation and equilibrium run parallel to the predictive coding approach. Both approaches' central insight is that prior knowledge generates predictions and controls behavior. If this is unsuccessful and a discrepancy between the actual feedback and the predicted one occurs, this discrepancy is passed back to the knowledge base, which is updated accordingly. Both approaches clearly propose that perception and cognition are construed as an active process of the mind and not as a purely reactive process to incoming signals.

Regarding the connection to motor development, as mentioned earlier, Piaget proposed that the schemas by which infants interact with their environment derive from their sensorimotor experiences. In this sense, he linked motor experiences with conceptual knowledge, which serves as a basis for infants' predictions. In a study that provides direct evidence for such a link, 9-month-olds familiarized themselves with a three-dimensional object (according to Shepard & Metzler, 1971) by rotating the object with their hands, then were tested with the familiar object from a novel view and a mirror version (Kelch et al., 2021). If infants could form an internal representation of the object from their manual experience and mentally rotate this representation, they would recognize the correspondence of the internal representation with the object seen from a novel view, but not with the mirror object. Indeed, infants showed significantly different looking times to the test objects, thus differentiating between them. However, this was only the case in crawling infants. Thus, infants' manual and locomotion experiences were associated with their ability to predict the correct version of the Shepard-Metzler object. In another study, motor achievements even seemed to play a causal role in driving infants' predictions about an object (Schwarzer et al., 2022). Overall, research suggests that motor experiences are involved in generating conceptual knowledge on which predictions are formed and updated.

Predictions based on internal motor models and motor experience

It is obvious that motor experiences might improve the internal models for infants' actions. In a study providing empirical evidence for this assumption, 9-month-olds were encouraged to repeatedly grasp a temporarily occluded moving object (Gehb et al., 2019). Infants' reaction times for grasping significantly decreased across trials, suggesting that they learned with increasing motor experience. Infants with the highest learning effect had the highest number of predictive grasps. In an additional task, which investigated infants' spontaneous manual object exploration procedures, those infants explored objects primarily by scanning the texture and contour of objects with their hands. Thus, increasing grasping experience and advanced manual object exploration behavior benefitted infants' active inferences, leading to improved predictive grasping.

Studies on infants' anticipation of others' actions also provide evidence of a facilitating effect of advanced motor skills for predictive action. These studies suggest that action prediction emerges with infants' own motor proficiencies (Gredebäck & Falck-Ytter, 2015). While 4-month-olds have poor reaching skills and fail to predict the goals of reaching actions, most 6-month-olds have developed the ability to reach for objects and can predict the goal of other people's reaching actions (Kanakogi & Itakura, 2011). Further evidence is provided by a study in which infants for whom crawling was their dominant form of locomotion predicted crawling sequences in other infants more accurately than walking sequences (Stapel et al., 2016). Overall, research suggests that infants' increasing fine and gross motor skills are very beneficial for generating and updating internal motor models, which enable them to improve their own action predictions and their understanding of others' actions.

CONCLUSION

Research has provided clear evidence that infants' predictions are based on their steadily improving abilities to detect statistical information in the environment, use and generate knowledge, and form and optimize internal motor models. Evidence also suggests that such improvements are strongly interwoven with infants' increasing motor abilities. New motor experiences affect the bases on which infants infer predictions and steadily change them to improved levels. We can assume that motor experiences in particular contribute to minimizing prediction error by refining active inferences. Studies support our hypothesis that the autonomous process of prediction in infancy (demonstrated by Emberson et al., 2015) is influenced by experience as a result of new motor skills. However, the question of how motor experiences exert such an influence has not been answered and is thus an important issue for researchers to address. Researchers might study neural processes of prediction in infants with high compared to low motor skills. Specific neuronal differences that are the result of infants' various motor skills could generate conclusions about the nature of the neural processes that mediate the connection between motor and predictive ability. Researchers might also investigate how different types of motor achievements change the way infants recognize statistics in the environment, generate knowledge, and improve internal motor models that serve as a basis for optimal predictions.

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