# 3

# The Development of Action Cognition

Antonia F. de C. Hamilton, Victoria Southgate, and Elisabeth Hill

**Abstract**

Humans learn motor skills over an extended period of time, in parallel with many other cognitive changes. The ways in which action cognition develops and links to social and executive cognition are under investigation. Recent literature is reviewed which finds evidence that infants advance from chaotic movement to adult-like patterns in the first two or three years of life, and that their motor performance continues to improve and develop into the teenage years. Studies of links between motor and cognitive systems suggest that motor skill is weakly linked to executive function and more robustly predicts social skill. Few, if any, models account directly for these patterns of results, so the different categories of models available are described.

## Introduction

Humans are born with very limited motor skills and yet, over an extended period, develop into independent individuals capable of the precise control of skilled actions. Throughout this process, an increasing ability to control actions may also contribute to the development of other cognitive faculties such as language, executive control, and social interaction. Thus, action cognition concerns two topics: how the motor control system actually works, and how motor control relates to other cognitive processes. We begin by reviewing adult models of the motor system because it is useful to understand the end point of a developmental process. Thereafter we discuss the developmental changes that occur on the way to that end point, both within the motor system and in links between motor and other cognitive systems. We conclude with a consideration of some of the different theoretical frameworks that have been put forward to account for the *development* of action cognition.

From “The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,”
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

## Control of Human Movement

The task of reaching out to pick up a toothbrush, applying toothpaste, and brushing one's teeth may seem trivial to the adult who does this daily without much thought. However, learning this skill is not simple. Children develop some motor skills rapidly after birth, but many take years before expertise is fully achieved. To control a highly nonlinear and redundant system of muscles and bones in an efficient fashion, their motor systems must contend with signaling delays and sensorimotor noise (Franklin and Wolpert 2011). Despite this complexity, a preschool child can easily surpass the visuomotor skill of the best robots available today. The study of action cognition is the study of the information-processing systems that underpin motor abilities. While it draws heavily on basic computational motor control, action cognition[1] includes more abstract processes, such as motor planning and motor sequencing, which are sometimes studied in relation to executive control. It is important to explore the relationship between action cognition and other cognitive systems, in particular executive function and social cognition.

A large number of different models have been proposed to understand sensorimotor control in typical adults, and from these, two major categories of model emerge. Computational models describe human movement in terms of optimal feedback control (Todorov and Jordan 2002) and forward/inverse models (Kawato and Wolpert 1998), considering in detail the type of engineering required to control the human motor system. An alternative approach simplifies control to the idea of an equilibrium point and suggests that the spring-like properties of the musculature can be adjusted to move the equilibrium of the arm (Feldman et al. 1998). A similar principle is found in the more recent active inference model (Friston et al. 2011). However, a key difference between these two classes of models concerns whether prediction is separate to or fully integrated with control (Pickering and Clark 2014). We will draw primarily from the former class of models, because they have been tested in more detail in developmental populations.

To summarize current knowledge about the development of motor systems and action cognition, we will refer to recent studies in this area. The vast majority of published papers on motor development focus on clinically relevant behaviors (e.g., walking, writing) without regard to the underlying cognition. Here our discussion focuses on performance of specific motor tasks that link closely to particular computational components of motor control. We distinguish between multisensory integration, visuomotor mapping, forward models, motor planning, and action comprehension, asking how each develops from infancy to adulthood.

---

[1] The term "cognition" is used as a synonym for "information processing." It does not imply a particular symbolic form of representation or a contrast to "affective" information but rather refers simply to any neural patterns of information between sensory input and muscle activation.

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

## Multisensory Integration

The human brain has many sources of sensory information which allow it to determine the current state of the world (e.g., visual, tactile, proprioceptive, and auditory input channels). A single physical event often impacts on many channels at once, and thus detecting congruency between different input channels and integrating inputs is helpful in building an accurate model of the state of the world. In adults, these different sensory information sources are integrated in a Bayes-optimal fashion (Ernst and Banks 2002). However, it is not yet clear how infants and children learn to integrate different senses. At a very young age, infants are sensitive to contingencies between different sensory modalities. An early study demonstrated that five-month-old children prefer to view a video of their own leg movements than a video of time-delayed leg movements (Bahrick and Watson 1985). However, this study did not distinguish which modalities (visual, tactile, proprioceptive, motor) are focused on by the infants.

Studies of visual and tactile integration suggest that this pairing is important from a very early age. Newborns (12–103 hrs old) prefer to view a face that is touched in sync with a touch to the infant's own face, than a face which is touched out of sync (Filippetti et al. 2013). This suggests they are able to detect synchrony between a face touch and a visual event. Similarly, seven-month-old infants prefer viewing a leg touched in sync with touches to their own leg (Zmyj et al. 2011), and the strength of this effect increases from seven to ten months. The integration of postural, visual, and tactile information also improves over the six- to ten-month age range, as shown by changes to somatosensory-evoked potentials in infants (Rigato et al. 2014). In older children (six-year-olds), visual-tactile integration can be similar to adults but is not mandatory, whereas adults cannot avoid integrating cues (Jovanovic and Drewing 2014). Visual-haptic cues for size discrimination are also not integrated in children before eight years of age (Gori et al. 2008). Similar results have been found for integration of different visual cues to depth (Nardini et al. 2010).

Visual-tactile-proprioceptive integration has also been examined using the rubber hand illusion (Botvinick and Cohen 1998). In older children (four- to seven-year-olds), the illusion is present and its magnitude remains constant over this age range (Cowie et al. 2013). However, the same children showed larger errors than adults in pointing to the true location of their hand, suggesting that visual-proprioceptive integration has not yet matured in this group. Further evidence of late maturation of visual-proprioceptive integration was found in a study of 7- to 13-year-old children in a hand localization task (King et al. 2010). Younger children in the sample were more reliant on visual information, which resulted in larger proprioceptive errors. A further study showed that noisy proprioceptive information could account for worse motor performance in six-year-olds compared to 12-year-olds (King et al. 2012). Together,

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

these studies suggest very early sensitivity to sensorimotor congruency, together with very protracted development of the ability to integrate the senses.

## Visuomotor Mapping

To obtain accurate control of hand actions, an infant needs more than multisensory integration; it must link motor commands and sensory input. This process is central to action cognition and has been studied from a variety of perspectives. A substantial number of studies that recorded from single neurons in monkeys found an occipito-parietal premotor pathway with a core role in transforming visual signals to motor actions (Cisek and Kalaska 2010). Within this pathway, mirror neurons are active when participants perform and observe actions (Rizzolatti and Sinigaglia 2010). These neurons might provide a basic social mechanism for understanding other people (Gallese et al. 2004), but alternative interpretations are also available (Hamilton 2013a; Hickok and Hauser 2010). In cognitive terms, the link between visual and motor systems has been explored in the associative sequence learning model (Heyes 2001). Central to all these models is the idea that visual information (about objects in the world and the hand) must be mapped to motor information about the actions that the hand is performing. Specifically, the infant must learn to link the retinal image of a skin-colored moving shape to the motor outputs it sends to its own hand and arm muscles. This must involve transforming the retinal information into other, intermediate representations (e.g., visual primitives, kinematics, action goals, motor primitives). Such coordinate transforms have been studied in detail for spatial tasks (Andersen et al. 1997) but have been less often considered in studies of action cognition. In particular, it is not yet known what types of intermediate representation are required for action cognition or how these can best be studied. Nevertheless, it is clear that infants can learn and use visuomotor mappings. For example, the more opportunity infants have to acquire a visuomotor mapping for leg actions (via live video feed of their own legs), the more active their motor system becomes when they observe leg actions (de Klerk et al. 2014). Thus, forming early links between visual images and motor systems is critical to the developing motor system and may also contribute to social cognition.

There is evidence that building robust visual motor mappings is important for infants, even from the earliest days of life. Neonates (10–24 days old) will move their arm to keep it within a beam of light where they can see it (van der Meer 1997). Around four months of age, infants begin to make reaching movements toward objects, but their hand trajectories do not follow a smooth, adult-like path until at least three years of age, after which it continues to improve (Konczak and Dichgans 1997). The development of grasping is also prolonged. For example, an adult will typically use a large grip aperture when reaching for an orange but a small grip aperture when reaching for a grape. Infants reaching for objects of different sizes always use the same grip aperture

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

at six months, but begin to scale their grip to the object by 13 months (von Hofsten and Ronnqvist 1988). One recent study suggests that four- to eight-month-old infants grasp as if their eyes were shut, relying on haptic cues; they only develop visual control of grasp by 24 months (Karl and Whishaw 2014). A study of four- to 12-year-olds reaching and grasping for objects showed clear improvements in trajectory and smoothness over this age range, with only the oldest children showing adult-like patterns of grip aperture scaling when reaching in the dark (Kuhtz-Buschbeck et al. 1998).

Another way to examine visuomotor mappings is to change these mappings, by asking a participant to make movements but giving false feedback about the location of the hand. Adults can adapt when a rotation of 45° is applied to the visual feedback given as the participant makes center-out movements, and then show aftereffects in the opposite direction when the false feedback is removed (Krakauer et al. 1999). The same method has been used to examine visuomotor transformation in four- to ten-year-old children. Results show that these children adapt to the new feedback like adults; however, the younger children showed smaller aftereffects when the false feedback was removed (Contreras-Vidal et al. 2005). This implies that younger children may have a broader tuning function in their visuomotor mapping than older children and adults. Overall, these studies show similarities to the studies of multisensory integration: early disorganized movements take on a recognizable pattern over the first year of life, and refinement of these movements continues for over a decade as the child gradually acquires adult levels of performance.

## Prediction and Planning

A major challenge in motor control is the inherent delays in the visuomotor system. Sending a signal from motor cortex to the muscle takes around 20–30 msec (Matthews 1991), with another 25 msec required to translate that signal into a change in muscle force (Ito et al. 2004). If a visual input is required, delay in retinal and early visual systems must also be considered, giving rise to a delay in involuntary visual responses of around 110–150 msec (Day and Lyon 2000). Forward models or predictors can be used to circumvent these delays; that is, a copy of the outgoing motor command (efference copy) is used to predict what the sensory consequences of an action should be, and the predicted consequences are compared with the actual consequences (Davidson and Wolpert 2003; Miall and Wolpert 1996). One of the clearest examples of the use of forward models in the motor system can be seen in the programming of grip force. If you need to pick a raspberry from a bush without crushing it, it is important to grip inward and pull the fruit away from the bush with just the right force and timing. Studies in adults have revealed that grip force (the force inward between the finger and thumb) is closely correlated to load force (the upward force against gravity) when an object is lifted (Johansson and Cole 1992). This can best be explained by the use of a forward model in which the

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

motor command to increase load force is also used to generate a prediction of the required grip force, so that grip and load can be controlled in parallel (Davidson and Wolpert 2003).

Studies of the development of grip force and load force over childhood demonstrate a very protracted developmental trajectory. The correlation between grip force and load force increases gradually over two to eight years of age (Forssberg et al. 1992) and continues to improve up to 14 years of age (Bleyenheuft and Thonnard 2010). Grip force dexterity in the more complex task of compressing a spring also improves over the four- to 16-year age range (Dayanidhi et al. 2013). A different way to measure predictive processes is to examine stability to unloading. In these tasks, a participant holds a heavy object in his/her left hand, thus requiring activation of muscles in the left arm to hold the object stable. In different trials, either an experimenter lifts the object from the participant's left hand (other-lift) or the participant lifts the object with their right hand (self-lift). In a self-lift, a participant is normally able to relax the left arm at just the same time as the object lifts, thus holding the left hand stable. In contrast, the timing of the other-lift cannot be predicted and so muscle activation in the left hand remains high for longer, with the left hand moving upward as the object is lifted. Performance on this task improves substantially from 4–16 years of age, but even 16-year-olds do not demonstrate the same level of performance as adults (Barlaam et al. 2012; Schmitz et al. 2002).

While predictive processes in motor control are helpful on a very short timescale (hundreds of milliseconds), planning processes can help performance on a longer timescale. One aspect of longer-term planning is seen in chaining tasks, where the kinematics of an action differs according to the next action performed. For example, a grasp followed by a throw has different kinematics during grasping compared to a grasp followed by a placing action (Becchio et al. 2012; Johnson-Frey et al. 2004). This is true for school-age children (Cattaneo et al. 2007; Fabbri-Destro et al. 2009) as well as ten-month-old infants (Claxton et al. 2003); however, detailed developmental studies have not been performed. More is known about planning based on end-state comfort. For example, when lifting a bar to place it in a particular location, adults will often begin the action with an awkward posture so as to end their action in a comfortable posture (Rosenbaum et al. 1990). The effect of end-state comfort provides a measure of action planning, and performance improves from three to ten years of age (Jongbloed-Pereboom et al. 2013; Stöckel et al. 2012; Weigelt and Schack 2010). Overall, these studies illustrate the very gradual development of predictive and planning abilities in the motor system, with changes in performance continuing up to 16 years of age.

## Comprehension of Other People's Actions

An important component of action cognition is social (i.e., the ability to understand what another person is doing now and intends to do next when viewing

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

their actions). Many studies have examined how this process develops in infancy and how it relates to other skills. From a young age, infants are able to interpret others' actions as movements directed toward goals and they use a variety of cues to identify a goal-directed action (Hernik and Southgate 2012). The dominant theory in this area suggests that if mirror neurons are central to action understanding (Gallese et al. 2004), then an infant's ability to understand an observed action should be dependent on their ability to perform that action. Data in support of this show links between performance and comprehension of actions. For example, three-month-old infants are not yet able to reach and grasp objects themselves and do not appear to understand actions as goal directed (Sommerville et al. 2005). However, if three-month-olds are provided with experience of grasping for objects by wearing Velcro gloves, which help them to pick up objects in their vicinity, they subsequently evidence an understanding that an observed reach and grasp action is goal directed (Skerry et al. 2013; Sommerville et al. 2005). Numerous other studies also demonstrate a relationship between developing action skill and various measures of action understanding (Cannon and Woodward 2012; Kanakogi and Itakura 2011).

One difficulty with these studies is that it is not always clear what it means for an infant (or an adult) to understand an action. Is it enough to predict what is next, or is a more elaborate representation of intention required? There is evidence that motor and mirror systems have a role in the former (Southgate et al. 2009, 2010, 2014). However, it seems that infants may also recruit their motor system during the prediction of others' actions that are outside of their own motor repertoire (Southgate and Begus 2013; Southgate et al. 2008). Thus, while infants' own motor skill does appear to influence their action understanding, the mechanisms mediating this relationship are unclear. There are also several reasons to believe that, at least in adults, intention understanding requires more than just motor prediction (Csibra 2007; Spunt et al. 2010). The relationship between motor and social cognition will be discussed in more detail in the next section.

### Summary

Action cognition encompasses a variety of skills and computational components which must work together to allow coordinated and efficient action. Developmental studies suggest that infants rapidly learn motor skills in the first year of life, moving from helplessness to a state with some basic control systems in place. However, the acquisition of full motor skill remains very protracted. Even everyday skills, such as grasping objects, draw on a complex system for visuomotor transformation and predictive control, and performance continues to develop and improve into adolescence. Developmental trajectories for motor skills are likely to be nonlinear—with progress in an area followed by stagnation, followed by more progress—and different motor skills do not develop in synchrony, even in children.

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

## How Does Action Cognition Relate to Other Types of Development?

Learning a new motor skill can change how a child engages with the world as well as how the world engages with a child. For example, an infant who can grasp an object might now perceive the potential of a cup for grasping in a way that a younger child might not. The grasping infant may also receive different social inputs from adults, who might place objects within reach (or remove them) and talk about the objects differently. Thus, learning a new motor skill has the potential to impact both a child's cognitive development and social development. Here we review work in this area to trace how different cognitive skills might be linked.

### Intellectual and Executive Development

There are many reasons to believe that motor and intellectual skills are connected. In longitudinal studies, motor skill has been linked to later motor, social, physical, and mental health outcomes as well as to academic achievement (Bart et al. 2007; Ekornås et al. 2010; Emck et al. 2011). Several studies have focused particularly on executive function—a broad term used to describe skills, including working memory, inhibition, and cognitive flexibility (Diamond 2013), related to measures of intelligence. Some aspects of executive control can be seen even in infancy (Johnson 2012) but the development of these skills continues into adulthood (Best and Miller 2010). There is mixed evidence for a relationship between executive function skills and motor skills. Five-year-olds with motor difficulties show differences in executive function measured one year later (Michel et al. 2011). In a study of 100 typical seven-year-olds, only some correlations between executive function and motor performance were reliable (Roebers and Kauer 2009). Reliable but small correlations were also reported in a study of motor skill and intelligence in 250 children (Jenni et al. 2013). However, other studies report positive associations. For example, throwing and catching skills correlated in particular with IQ (Rigoli et al. 2012a), an effect that might be mediated by working memory (Rigoli et al. 2012b). Other work suggests that links between motor and cognitive skills might be mediated by visual performance (Davis et al. 2011).

Some theories claim strong links between motor skill, cognitive skill, and the development of the cerebellum (Diamond 2000; Wang et al. 2014). For example, in children with cerebellar tumors, there is a correlation between motor and cognitive skills (Davis et al. 2010), and cerebellar function has been linked to autism (Wang et al. 2014); direct evidence in typical children, however, is limited. Developmental coordination disorder (DCD) can also be examined as a test case. A study by van Swieten et al. (2010) demonstrated developmentally inappropriate *motor* planning in six- to 13-year-old children with DCD, but

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

appropriate *executive* planning (using a Tower of London task) in seven- to 11-year-olds in this group. Pratt et al. (2014) identified, however, significant difficulties with both types of planning in a different group of children with DCD, compared by age and IQ to typically developing children. Leonard and Hill (2014) show that children with DCD performed worse than typically developing controls on *nonverbal* measures of working memory, inhibition, planning, and fluency, but not on tests of switching or verbal equivalents of the same tasks. Overall, these studies give mixed support to the claim that motor cognition and executive function are linked. There may be weak correlations between these cognitive systems, but the association is not a tight one.

## Social Development

Much better evidence is available to suggest that motor skill contributes to social development. During infancy, motor development can affect how infants interact with individuals around them. For example, as infants improve in manipulating objects, they also show altered patterns of attention to others in the environment (Libertus and Needham 2010). The onset of crawling and walking is linked to greater joint attention and social referencing, perhaps because of the altered type and number of interactions the young child is then able to have with its caregivers (Campos et al. 2000; Karasik et al. 2011; Leonard and Hill 2014). Specifically, the ability to move around and explore the environment as well as manipulating objects and sharing them with others provides more opportunities to engage in joint attention and changes the types of vocalizations and expressions the infant receives from the caregiver. Evidence for relationships between motor development, language, and social communication skills can be seen from the outset in typical development through the tight coupling of motor and language milestones throughout infancy (Iverson 2010). There is also a feedback loop between produced and heard speech: children with autism produce less speech and, in return, receive less speech input from their caregivers (Warlaumont et al. 2014). Thus, motor skills can directly influence the child's social environment and opportunities to develop social skills.

Many studies of links between action cognition and other types of cognition have examined children with developmental disorders, in particular autism spectrum conditions diagnosed on the basis of poor social cognition. As many as 80% of children with autism have substantial motor difficulties (Green et al. 2009), and interest in the links between autism and motor cognition is increasing (Fournier et al. 2010; Gowen and Hamilton 2012). In particular, there is evidence for dyspraxia (poor performance of skilled hand actions) in autism beyond other possible motor impairments (MacNeil and Mostofsky 2012; Mostofsky et al. 2006). Infant siblings at risk of developing autism demonstrated differences in standardized motor tasks and face-processing tasks (Leonard et al. 2013). In children at high risk of developing autism, greater

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

autism symptoms were also seen in those with poorer motor skills (Bhat et al. 2012; Leonard and Hill 2014).

Despite clear links between overall levels of motor and social skills, it is harder to identify specific differences in cognitive systems, and here results are more variable. Children with autism show poor performance in specific tasks involving motor planning in some studies (Hughes 1996) but not in others (Hamilton et al. 2007; van Swieten et al. 2010). Some studies report difficulties in chaining actions together in sequences (Cattaneo et al. 2007), but others do not (Pascolo and Cattarinussi 2012). Detailed testing of visuomotor adaptation in children with autism did not find group differences (Gidley Larson et al. 2008). Similar variability is found in studies of how children with autism understand other people's actions—a social component of motor cognition. Some studies report difficulties in answering questions about why a person performed an action (Boria et al. 2009) or in predicting what will come next in a movie (Zalla et al. 2010). Other studies, however, find no differences in the ability to make sense of hand gestures (Hamilton et al. 2007). Studies of imitation show intact performance on emulation tasks (copying the goal of an action) but poor performance on mimicry tasks (copying precise kinematic features) (Edwards 2014; Hamilton 2008). Some of these differences may be explicable in terms of links to executive function or top-down control (Wang and Hamilton 2012). Overall, there is no single aspect of motor cognition that can be directly linked to poor social cognition. More research is needed to understand how motor and social developmental processes interact.

### Summary

Overall, data show reliable but small links between motor cognition and executive function, and larger more robust links between motor cognition and social cognition. In particular, changes in motor skill seem to drive changes in the child's social environment and predict later performance in situations involving communication and interaction. However, it is less clear what specific cognitive processes drive these effects. To assign motor-social links to a single brain system (such as the mirror neuron system) is probably premature (Hamilton 2013b). Instead, it will be important to consider how different systems *interact* in development, and how the acquisition of one skill gives the child more opportunities to learn other skills, in a complex interplay between the child and the social environment.

## Theories for Understanding the Development of Action Cognition

There are many different theoretical frameworks under which we could try to make sense of the development of action cognition and its relationship to

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

social cognition. Here we provide a brief overview of the different options, before ending with suggestions for future directions.

## Cognitive Theories

The traditional way to understand information processing in the human brain is to develop cognitive or computational models that can reproduce that processing (Marr 1982). To understand action cognition, computational models provide a powerful way to test and explore the problems which the human brain must solve to move in the world (Franklin and Wolpert 2011). Similar computational mechanisms could be applied to social cognition: the motor control mechanisms that allow a person to predict and control a tennis racket might also allow a person to predict and control the actions of another person (Wolpert et al. 2003). Such models can incorporate gradual motor learning but do not say anything specific about development.

A related approach to action and cognition can be found in the mirror neuron framework (Rizzolatti and Sinigaglia 2010), which postulates how motor performance and action understanding could be linked to the same neural systems. The mirror neuron model has been set within a developmental context (Gallese et al. 2009), with strong claims that the failure to develop mirror systems in autism might account for difficulties in social cognition (for a critique, see Hamilton 2013b). This account also places a strong emphasis on prenatal and innate mechanisms of action and cognition, and does not leave much space for development after birth. Thus, neither of these models has much to say about the rapid improvements in action cognition during the first year of life.

One way to expand the cognitive approach, so as to consider developmental change, is to study developmental disorders. Developmental causal modeling (Morton 2004) and the ACORN framework (Moore and George 2011) provide tools for specifying and testing cognitive models of child development and developmental disorders. Using these tools, a developmental process can be formally specified in terms of the biological, neural, and cognitive changes that take place at different developmental time points, as well as the ways in which these influence each other. Such a formal model is more amenable to testing and clinical use than more weakly specified theories. For example, a developmental causal model of autism suggests that a primary difficulty in theory of mind can account for many of the observed difficulties in social cognition (Frith et al. 1991), and this has been tested in detail (U. Frith 2012). A key question for cognitive approaches to development is to identify the different modular systems and to determine if and how they might interact. For example, is the development of motor systems essential to theory of mind (Gallese et al. 2009), or not (U. Frith 2012)? It would be possible to place these questions and the relevant data on action cognition into a more formal modeling framework of causation to test out theories of developmental change, but this has yet to be attempted.

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

### Interactionist Theories

An alternative approach that is gaining ground is to focus the study of child development on the process of development itself (Karmiloff-Smith 2012). Rather than starting from the adult end state and considering the child as an adult with some bits missing, this approach considers fully how new capacities can emerge out of the interaction between the infant and the social-motor environment. In the motor domain, dynamical systems models have been used to describe how motor skills emerge in infants from the interaction of the child and the environment (Thelen and Smith 1996). In social cognition, embedded and embodied accounts (Reddy 2008) view social skills as emerging from the interaction between infant and caregiver, rather than being internalized by the infant. A key prediction in these models is that developmental changes emerge out of the relationship between the child and the environment. For example, if a child who can walk obtains different physical and social inputs to a child who cannot walk, this will initiate the development of particular social and motor skills. The emphasis here is on a longitudinal, two-way relationship between the child and the social-physical world.

Interactionist theories are part of the push toward thinking of cognition not in isolation, but grounded in reality, embodied in the world, and created by the interaction between child and world. This push is similar to the new emphasis on "second person neuroscience" (Schilbach et al. 2013), where the emphasis is strongly on the interrelation between the developing child and that child's social-motor environment. This is a promising approach which is coherent with reports of close links between the child's social-motor experience and their further development (Leonard and Hill 2014)). However, the major limitation of this approach is its complexity. If the decomposition of behavior according to cognitive processes is abandoned, it is not clear how development should be decomposed. Yet without any decomposition, the problem of understanding a process and formulating testable models is difficult. Overall, interactionist models are intriguing but it remains very hard to find tractable experimental approaches to test their validity.

## Future Directions

In this review of the development of action cognition, data suggest that motor development is a very protracted process—one that is linked to other areas of cognition, in particular to the development of social skills. Two categories of key unanswered questions include:

1. What is the best framework for understanding the development of motor control? Can we break down motor control into specific cognitive processes and track the development of each? Or is this only feasible through a holistic, interactionist account?

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.

2. What processes link motor and social cognition? Are there specific cognitive mechanisms which might be shared between motor and social cognition and, if so, what are they? Alternatively, are the associations we observe in data between motor and social skills driven instead by changes in the child's opportunities to learn, or other facets of the environment?

To address these questions, more data is needed on how motor cognition actually develops. In young children, it would be particularly helpful to consider the substantial individual differences that are apparent at certain ages (e.g., walking at nine vs. 18 months) but resolved at later ages (almost all four-year-olds can walk in a similar way). It is also critical to consider the interplay between the child and the environment. Longitudinal studies which track the child's skill and social surroundings over time would be particularly valuable in this regard. Finally, the study of children with a range of developmental disorders (not just autism) are needed to understand why motor cognition sometimes goes wrong and what the implications of this are for both typical and atypical development.

From "The Pragmatic Turn: Toward Action-Oriented Views in Cognitive Science,"
Andreas K. Engel, Karl J. Friston, and Danica Kragic, eds. 2016. Strüngmann Forum Reports, vol. 18,
series ed. J. Lupp. Cambridge, MA: MIT Press. ISBN 978-0-262-03432-6.