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SELF-BY-DOING: THE ROLE OF ACTION FOR SELF-ACQUISITION

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The experience of the phenomenal, so-called "minimal self" is commonly taken as a given and as a core requirement for the performance of goal-directed action. We discuss evidence suggesting the exact opposite scenario. In fact, evidence for truly goal-directed movements has been reported no earlier than around 9 months of age, and unequivocal signs of self-other distinction and action-ownership seem to emerge even later. This suggests that the self is not a given but that it emerges through active interaction with one's physical and social environment. Hence, the self is a result, rather than a precondition of intentional action. We discuss evidence that the self-construction process comprises of ideomotor learning, which builds up a database for intentional action selection, and predictive coding, which allows for action evaluation. We also speculate that rudimentary aspects of agency experience may precede the experience of action-ownership.

Keywords: goal-directed action, minimal self, agency, infancy, cognitive development, self, ideomotor theory

THE MINIMAL SELF

The goal-directedness of our actions is such an integral part of our life that we normally take it for granted. Yet, it is this special quality of behavior that enables the

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voluntary manipulation of the social and physical reality to suit our needs. Since the skill with which humans can manipulate their environment and assess the goals of others is arguably what sets us apart from other beings (Call & Tamasello, 2008; Premack & Woodruff, 1978), goal-directedness both in actions and the perception thereof should be considered the core characteristic of the human condition. Accordingly, philosophers like Gallagher (2000) claim that volition or agency is an integral part of what is called the "minimal self," which is thought to consist of "a consciousness of oneself as an immediate subject of experience, unextended in time. The minimal self almost certainly depends on brain processes and an ecologically embedded body, but one does not have to know or be aware of this to have an experience that still counts as a self-experience" (Gallagher, 2000, p. 15). The minimal self is often distinguished from the "narrative self," which refers to the ability to tell stories about oneself, fueled by self-related memories and the application of impression-management strategies (e.g., Gallagher, 2000; Tsakiris, Schütz-Bosbach, & Gallagher, 2007; Zelazo, 1996). Given our focus on the development of the self in the earliest years of infancy and childhood, during which any assessment necessarily relies on nonverbal behavior, we will not further consider the "narrative self" but restrict our discussion to the "minimal self" instead.

The minimal self is assumed to comprise of two, commonly strongly correlated experiential components: the sense of agency, which refers to the sense that it is me who is causing or actively generating an action, and the sense of ownership, which refers to the sense that it is my body that is involved in this experience (e.g., Gallagher, 2000; Tsakiris et al., 2007). While experienced agency and ownership are typically highly correlated in experiential flow, they can be dissociated under particular experimental circumstances, even in healthy subjects. A famous example is the Rubber Hand Illusion (Botvinick & Cohen, 1998), which is obtained by placing a rubber hand in front of a participant, right above his or her corresponding real hand that is however covered from view. If then the visible rubber hand in the unseen real hand are stroked in synchrony, participants experience the rubber hand as part of their own body (i.e., they have an ownership experience, often without perceived agency; e.g., Kalckert & Ehrsson, 2012). Furthermore, schizophrenic patients can suffer from dissociations of agency and ownership, so called self-disorders, making it hard for them to distinguish if they themselves are the initiator/owner of their acts or another entity (e.g., Renes, Vermeulen, Kahn, Aarts, & van Haren, 2013; Synofzik, Their, Leube, Schlotterbeck, & Lindner, 2011; Tsakiris et al., 2007). Such dissociations suggest that the informational databases on which judgments of ownership and of agency rely, overlap to a considerable degree but are not identical. In any case, healthy humans are assumed to be equipped with a minimal self that integrates aspects of agency and ownership. The question we pursue in this article is where this minimal self comes from.

Self-theorists usually take the self for granted and explicitly or implicitly suppose that (some substantial portion of) it is with us from birth, if not earlier (e.g., Bruner, 1973; Butterworth & Hopkins, 1988; Meltzoff & Moore, 1997; Rizzolatti & Craighero, 2004; Rochat, 2001). The reasons for this assumption are not always clear; but authors often emphasize observations of what look like instrumental, goal-directed actions in newborns and very young infants, presumably because these are taken as signs of a (not necessarily conscious) sense of agency and/or because goal-directed action is implicitly assumed to presuppose a minimal self. Indeed, behaviors such as moving a hand toward the mouth (Butterworth & Hopkins, 1988) or orienting toward sound (Zelazo, Brody, & Chaika, 1984) are evident in neonates (e.g., Bertenthal, 1996; Meltzoff & Moore, 1997; von Hofsten, 2004). Slightly more demanding movements, such as grasping an interesting object, appear not much later, around 5 months of age (Bertenthal & Clifton, 1998; Clearfield & Thelen, 2001). If one includes conation as indicating a minimal self, it indeed seems to be apparent in newborns: the experience of an infant "wanting" milk can be irresistible for caregivers.

And yet, the self-as-a-given approach can be challenged and has been challenged on theoretical and empirical grounds. In the following, we will first discuss some of these challenges and then present a theoretical alternative that construes the self as an emerging property of sensorimotor/ideomotor learning. Finally, we will discuss some recent empirical and theoretical challenges of this approach as well and suggest a hybrid model that integrates ideomotor mechanisms with predictive-coding mechanisms.

EVIDENCE FOR ACTIVE SELF-ACQUISITION

The popular self-as-a-given approach has the disadvantage that it has prevented the development of testable models about its underlying mechanisms, which basically has rendered the scientific concept of the self a black box. Moreover, the intuitions and arguments that seemingly support this approach cannot be considered watertight. For instance, the observation of spontaneous imitation at birth (Meltzoff & Moore, 1977, 1983) was claimed to demonstrate intentional action and to require the abilities to (1) distinguish between self and non-self; (2) locate and intentionally use certain parts of one's body; and (3) recognize the similarity between the observed and one's own face, which in turn has been taken to imply a "primitive self-consciousness" and "a minimal self" (Gallagher, 2000). As we will elaborate in the next section, such an approach fails on several grounds. For one, what has been interpreted as intentional action at or soon after birth is more likely to represent stimulus-induced reflex-like behavior (Fisher & Lerner, 2005; Jones, 2009) rather than behavior driven by representations/anticipations of behavioral outcomes—a necessary hallmark of truly intentional behavior. As we will argue, unequivocal signs of truly goal-directed, intentional behavior emerge no earlier than around nine months of age, that is, much later than assumed by the self-as-a-given approach. For another, even if goal-directed, intentional action could be demonstrated right from, or even before birth, this would not necessarily imply the existence of any kind of self. As we will explain, the key criterion for counting behavior as goal-directed is the anticipation of its outcome, that is, the having of a goal. Whether the agent having this anticipation is able to engage in self-perception, subjective agency and ownership, is entirely irrelevant. As we will explain below, rather simple associative mechanisms are able to generate goal-directed behavior without the need to postulate any kind of "self."

An important argument for supporters of the self-as-a-given approach is the demonstration that infant behavior is sensitive to action-contingent effects. For instance, newborns adjust their sucking rate in response to their mothers' voice as ongoing conditional feedback (DeCasper & Fifer, 1980) and 2-month-olds pursue interesting action effects by intentionally varying their sucking rate (Rochat & Striano, 1999) or varying gaze direction (Watson, 1967; for a review, see Gergely & Watson, 1999). However, while these observations clearly point to the sensitivity of infants to action effects, they do not require the assumption that the infants actually carried out their movements in order to produce their effects. Adult studies have shown that actively producing any perceivable change in one's environment is rewarding (Eitam, Kennedy, & Higgins, 2013; Karsh & Eitam, 2015) and this can be taken to induce effectance motivation (White, 1959); the tendency to explore and change one's environment. Thus the action opportunities and the action effects offered in these experiments might merely increase the infant's activation level and thereby increase the frequency of reflexive or situationally conditioned responses. Another line of research shows that action effects can aid memory for actions from 2 months of age (e.g., Rovee & Rovee, 1969; for a review, see Rovee-Collier, 1999). During a learning phase in this type of research, in half of the infants one of their legs is connected by wire to a mobile, in such a way that the infant is able to move the mobile by kicking. During a later retention phase, 2-month-old infants showed increased kicking rates when presented with the moving mobile (as compared to infants who could not move the mobile during the learning phase) even if being tested two weeks later. However, interpretations of these findings in terms of conditioning-induced increases of arousal and/or entrainment are again difficult to rule out.

Another line of research that shows that infants are sensitive to action effects can be found in studies tapping into what one might call "violations of agency," wherein infants are shown contingent versus non-contingent video images of themselves (e.g., Papoušek & Papoušek, 1974). Several studies have demonstrated that at three months of age infants reliably detect the difference between contingent and incontingent displays (Field, 1979; Rochat & Morgan, 1995; for a comparable result in 9-week-olds see Reddy, Chisholm, Forrester, Conforti, & Mantiatopoulo, 2007), suggesting that at this age they are able to generate expectancies regarding the matching of proprioceptive and visual information—an important precondition for perceived agency. In studies on mirror self-recognition, participants are painted a colored dot on their nose without knowing. If they are then watching their face in a mirror, those that notice and try to remove the dot are considered as recognizing themselves (Gallup, 1970). No earlier than around 18 months of age, 50% of human participants (as well as some apes, dolphins, elephants, and even magpies; Prior, Schwarz, & Güntürkün, 2008) show such behavior (Amsterdam, 1972; Gallup, 1998; Gallup, Platek, & Spaulding, 2014; Stapel, van Wijk, Bekkering, & Hunnius, 2016). Interestingly, self-recognition can be found earlier for dynamic mirror presentations than for photographs (Courage, Edison, & Howe, 2004). This suggests that self-identification does not only rely on general expectations of the infants regarding their own appearance but also on online contingency information. In other words, selfhood is derived from perceived agency—the exact opposite sequence of what self-as-a-given approaches suggest. Self-recognition continues to develop at least until the fourth year of life, when children begin to master more advanced self-recognition tasks, such as delayed self-recognition in video or photograph format (Povinelli, Landau, & Perilloux, 1996). An interesting conclusion from these studies is that infants apparently learn to predict the sensory effects of their bodily movements before they are actually able to experience ownership of their mirror image.

Other observations have been taken to suggest that true goal-directed actions—wherein the means are clearly distinguishable from the goal and where outcome prediction is observable—start to appear no earlier than around 9 months of age (Baldwin, 1892; Claxton, Keen, & McCarty, 2003; Hauf, 2007; Piaget, 1936, 1952; Willatts, 1999; Woodward & Sommerville, 2000; Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009). Various findings suggest indeed that around that time young actors start to take expected action outcomes into account when deciding which action to perform. For instance, imitation in 9-month-olds is enhanced when salient action effects are present in the model's behavior (Hauf & Aschersleben, 2008; Klein, Hauf, & Aschersleben, 2006; for a review, see Elsner, 2007; Meltzoff, 2007): infants are more inclined to reproduce behaviors that have interesting action effects than those that do not. Moreover, 6-, 8- (Wang et al., 2012), and 10-month-olds (Kenward, 2010) anticipate their own action outcomes. By 8 months, infants show motor resonance when listening to previously self-produced action-related sounds (Paulus, Hinnius, van Elk, & Bekkering, 2011). Interestingly this effect has also been shown in 9-month-olds for action effects produced by others (Paulus, Hunnius, & Bekkering, 2013), which might be taken as an indication that other people's actions tend to be confused with one's own actions—an issue we will get back to later. In any case, there is evidence that from about 9 months of age on, the performance of actions tends to be preceded, and presumably driven by expectations about wanted action effects. Given that this is a necessary requirement to consider an action truly goal-directed, we can conclude that intentional action emerges around that time.

Direct evidence for a role of expected action effects in the action control of young agents was reported by Verschoor, Weidema, Biro, and Hommel (2010). During a first acquisition phase, these authors presented 9-, 12-, and 18-month-olds with a large touch-sensitive plate. The behavior of the participants was monitored and in one condition each spontaneous plate-touching action was made to elicit a salient audiovisual event (E1). In another condition, the participant's caregiver prevented the participant from touching the plate while another audiovisual event (E2) was presented. In other words, E1 was actively produced by a goal-directed action while E2 was not. For reasons to be elaborated in the next section, the expectation was that this would create an association between the goal-directed action and E1, so that the action was not only expected to produce E1 but also selected by activating the representation of E1 (indicating truly goal-directed action control). If so, presenting E1 in the following test phase should reactivate E1's representation and thereby reactivate the corresponding plate-touching action, while presenting E2 should not have such an effect. As predicted, plate-touching was faster (and in the 18-month-olds more frequent) when E1 was presented than when E2 was presented (cf. Elsner & Aschersleben, 2003). This observation can be taken to provide first evidence for the acquisition of bidirectional associations between actions and their expected outcomes, and for a role of these associations in action control from about 9 months of age on.

While the demonstration of outcome anticipations in 9-month-olds fits with previous indications of the emergence of voluntary action control around that age, it does not rule out the possibility that younger infants can show the same ability. It would certainly be possible to repeat the study with even younger infants, but given that the action investigated by Verschoor et al. (2010) was rather high in motor demands, a possible absence of significant effect in a target group with insufficiently developed motor skills could not be considered sufficiently diagnostic. To circumvent that problem, Verschoor, Spapé, Biro, and Hommel (2013) investigated 7- and 12-month-olds (and adults) by using a much more natural and easier to master goal-directed activity, namely, eye movements. During the first acquisition phase, spontaneous saccades were elicited by presenting salient stimuli in the periphery left or right from the central fixation point. Each saccade to the left was followed by one particular tone (E1) and each saccade to the right was followed by another tone (E2). Again, the idea was that left-going saccades would become associated with E1, and right-going saccades with E2, so that presenting E1 in a later test phase would increase the speed to look to the left (and/or slow down looking to the right) and presenting E2 would have the opposite effect. Interestingly, this predicted effect was observed in the 12-month-olds and in adults, but not in the 7-month-olds. Together with the other observations discussed above, this supports the conclusion that intentional action emerges around 9 months of age.

What are the reasons why actions guided by the expected outcomes of actions do not occur earlier? The perhaps most obvious possibility is that infants may not yet be able to associate actions with outcomes, so that outcome anticipations cannot be formed and, therefore, cannot be used for action control for other trivial reasons. However, three lines of research suggest that this possibility is unlikely to apply. First, Verschoor at al. (2013) did not only register the speed and direction of saccades but they also monitored pupillary dilations, which are commonly taken to reflect surprise and, thus, discrepancy from expectation. Surprisingly, participants from all three age groups exhibited significantly larger pupils during saccades that went into a direction that did not fit with the direction implied by the effect tone. For instance, if left-going saccades produced E1 in the acquisition phase, participants that were saccading to the right when being presented with E1 would show dilated pupils, suggesting that they expected another action to follow. Separate tests revealed that this effect was statistically significant in the 7-month-olds,[1] even

1. When the adult subjects were asked if they were aware of the mapping presented during acquisition more than half replied they were not. Since they showed the same effect, this probably means that the pupillary effects reflecting outcome predicting are a measure of an implicit feeling of agency rather than an explicit judgement.

though they did not show any slowdown of the respective saccade. This suggests that they had acquired the association between the particular actions (saccades) and the respective auditory effects, but this association did not yet impact the selection of actions.

A second reason to reject the idea that infants below 9 months of age are unable to associate actions with outcomes is that infants have been demonstrated to make predictions about others' action outcomes quite some time before they show evidence of truly intentional action themselves. Woodward (1998) repeatedly presented 9-month-olds with a human actor grabbing one of two toys, each in a particular location. Next, the toys' locations were switched and participants were exposed to an actor grabbing either the old toy in the new location or the new toy in the old location. Infants dishabituated more to the condition in which a new toy was being grabbed than to the condition in which the old toy in a new location was being grabbed, suggesting that they predicted the actor to continue grasping the same toy irrespective of the location. With appropriate controls, this paradigm can be taken as evidence for goal/outcome prediction for other humans' actions in infants. Interestingly for our purposes, later studies have demonstrated successful goal prediction in infants around 6 months of age (e.g., Biro & Leslie, 2007; Kamewari, Kato, Kanda, Ishiguro, & Hiraki, 2005; Woodward, 1999), and some studies found similar effects even at 3.5 months of age (Sommerville, Woodward, & Needham, 2005). Again, salient action effects in others' behavior have been shown to aid third person goal prediction (e.g., Biro & Leslie, 2007; Jovanovic, Király, Elsner, Gergely, Prinz, & Aschersleben, 2007; for a review, see Hauf, 2007) even for unfamiliar actions (Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003).

Third, several studies have shown that the infant's own action experience (and thus action-effect knowledge) affects the prediction of third-person goal-directed action (e.g., Biro, Verschoor, Coalter, & Leslie, 2014; Hauf, Aschersleben, & Prinz, 2007; Sommerville & Woodward, 2005a, 2005b), and aspects of this ability have been observed in 3-month-olds (Sommerville et al., 2005), 6-month-olds (Nyström, 2008), and 8-month-olds (Nyström, Ljunghammar, Rosander, & von Hofsten, 2011; Paulus, Hunnius, & Bekkering, 2013) already. Again, these observations suggest that infants are able to predict action outcomes before they are able to control their own actions in a goal-directed manner.

Taken altogether, we conclude that the ability to perform goal-directed actions (i.e., actions that are driven by expectations of their outcomes) emerges around 9 months of age, while it remains unclear whether the ability to successfully predict action outcomes, which has been claimed to provide the key criterion for sensing agency and ownership (Gallagher, 2000), is available at birth. Clear-cut signs of self-identification occur even later, around 18 months of age. This pattern is inconsistent with the claim that the self, as expressed by the ability to perform intentional, goal-directed actions, is with us from birth (e.g., Gallagher, 2000). Moreover, the ability to carry out goal-directed actions is not synchronized, but rather precedes the ability to self-identify, suggesting that if anything, intentional action is a prerequisite rather than an indication or mere expression of selfhood. This scenario puts great emphasis on the development of goal-directed action and the information it provides the agent with. We therefore need to ask what mechanisms are at the basis of this development, and how they establish a cognitive database that allows actions to become goal-directed and the agent to acquire a minimal self. While a fully fletched theory is not yet available, we will discuss two important components of such a theory: ideomotor leaning and predictive coding.

IDEOMOTOR LEARNING

Goal-directed actions are commonly defined as movements directed toward attaining a future desired state—the goal, that is. This definition requires the respective movement to be driven or activated by some representation of the environmental change that the movement is likely to create, which in turn can be considered a sort of anticipation of the expected effect of the movement. In other words, it is the (not necessarily conscious) anticipation of its effect(s) that renders a movement a goal-directed, intentional action. Being able to anticipate the likely outcome of an action presupposes knowledge about the relationship between the action and its effects, which must have been acquired previously (be it through own experience or the observation of action-effect contingencies in others). It is this reliance of intentional action control on sensorimotor experience that William James had in mind when writing: "...if, in voluntary action properly so-called, the act must be foreseen, it follows that no creature not endowed with divinatory power can perform an act voluntarily for the first time" (1890, p. 487; see also Harless, 1861; Lotze, 1852).

The ideomotor theory developed by Lotze, Harless, James, and others suggests that knowledge about sensorimotor contingencies is acquired on the fly: whenever people move, they automatically and unintentionally create bidirectional associations between the perceived sensory effects and the motor pattern producing them—ideomotor learning. Such action-effect associations provide the knowledge needed to bring movements under voluntary control; once acquired, the agent can produce a movement by "thinking of" a perceptual effect, which reactivates the effect's internal representation and, as a consequence, the associated action. The collection of such associations may start very early in life since infants start to motor-babble (i.e., produce random, reflexive movements) in utero (Meltzoff & Moore, 1997). Any sensorimotor activity, be it reflexive or explorative in nature, would thus provide opportunities to acquire movement/action-effect associations and steadily increase the pool of possible action goals, that is, action effects to be created by performing the associated action. James (1890) already considered bidirectional action-effect associations the fundamental building blocks of intentional action, but ideomotor theory was later refined by Greenwald (1970), Prinz (1990, 1997), Hommel (1996; Elsner & Hommel, 2001), and others and is now part of a broader theoretical framework stressing the interplay between perception and action (Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Meltzoff, 2007; Meltzoff & Prinz, 2002).

Greenwald (1970) was the first to propose a paradigm that directly assesses the assumed bidirectionality of action-effects. He suggested letting people acquire action-effect associations by exposing them to novel sensory consequences of their actions, and then test whether this motor-sensory experience (through the hypothesized ideomotor-learning mechanism) rendered effect stimuli effective cues of the action they were produced by. If experiencing the contingency between a particular action and a particular stimulus (the action effect) would indeed create a bidirectional association between the representation of the action and the representation of the stimulus, presenting the stimulus should reactivate its representation, which in turn should prime the associated action. Elsner and Hommel (2001) followed this suggestion in a study on adults. In a first acquisition phase, participants carried out self-chosen left and right keypresses in response to a visual trigger stimulus. Each key press produced a particular sound (e.g., left key a low tone, right key a high tone). Even though these sounds were irrelevant to the task, it was predicted that participants would nevertheless spontaneously acquire bidirectional associations between the representations of the keypresses and the tones. In a subsequent test phase, participants could again freely choose left and right key presses, but now the visual trigger was accompanied by randomly chosen tones of the same frequencies as in the acquisition phase. As expected, participants were quicker and more likely to choose the action that previously had produced the currently presented trigger tone (e.g., they preferred pressing the left over pressing the right key when being presented with a low tone), suggesting that key presses and tones were indeed associated in a bidirectional fashion and instrumental for action control.

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These findings encouraged numerous demonstrations of bidirectional action-effect acquisition in humans ranging from 4-year-olds (Eenshuistra, Weidema, & Hommel, 2004; Kray, Eenshuistra, Kerstner, Weidema, & Hommel, 2006; Verschoor, Eenshuistra, Kray, Biro, & Hommel, 2011) to adults (e.g., Elsner & Hommel, 2001). Action-effect acquisition was found for a wide range of actions and effects (for a review, see Hommel & Elsner, 2009), suggesting that action-effect integration is a general phenomenon. Additionally, action-effect acquisition has been found after just one trial (Dutzi & Hommel, 2009), suggesting that the mechanism is fast-acting and implicit. Action-effect acquisition is modulated by the same factors that influence conditioning (e.g., temporal contiguity and contingency of movement and effect; Elsner & Hommel, 2004) and does not depend on voluntary attention (Band, Van Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; Dutzi & Hommel, 2009; Elsner & Hommel, 2001). Taken together with the fact that action-effect learning was also found in animals (see Elsner & Hommel, 2001), this suggests that action-effect integration it is a fairly low-level, automatic process (Elsner & Hommel, 2004). Findings from neuroimaging studies suggest that this process integrates the sensory codes of action effects (in the respective perceptual cortices; Kühn, Keizer, Rombouts, & Hommel, 2011) with action plans in the supplementary motor cortex via hippocampal bindings (Elsner et al., 2002; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008).

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The left part of Figure 1 captures the gist of the ideomotor scenario: carrying out movements/actions automatically integrates the underlying motor patterns with the sensory effects they are perceived to generate (ideomotor learning). Once the bidirectional association has been established, activating the representation of the action effect spread activation to the associated action (action selection), which under appropriate circumstances leads to action execution. We have seen that this scenario applies not only to adults and children, but to 9-month-old infants as well (Verschoor et al., 2010), as pairing and action with a novel action effect rendered the action effect a potent prime of the respective action in all these groups. Not so in 7-month-olds, however (Verschoor et al., 2013), which fits with the emerging consensus that the intentional action emerges around 9 months of age.

We can only speculate why intentional action selection emerges no earlier. We have emphasized already that this is unlikely to reflect the inability to create action-effect associations or to predict action-contingent events. Prinz (2012) has suggested that this developmental step might be related to what he calls a "dual representational ability." According to his reasoning, an actor must be able to properly perceive the current situation but at the same time has to have a separate representation of the goal in order to not only simply react to the current stimuli but perform goal-directed actions. Before a developing agent is able to do that, he or she attributes agency and agenda of control to others they perceive acting. Only through learning to mirror the observed actions oneself, the actor eventually acquires perceived agency and starts attributing agentive control to him- or herself. Hence, Prinz (2012) suggests that goal-directed action derives from social interactions. This possibility fits with the above-mentioned observations that action effects observed in others impact outcome prediction of the developing infant quite some time before he or she is able to carry out goal-directed actions him- or herself. If social exchange and the social experience of other people's actions is a necessary requirement for acquiring action control, it makes sense to assume that the latter follows the former, and that it does so relatively late in the process.

But other possibilities remain. For instance, dual representation may indeed be necessary to acquire intentional action control but it may be the slow development of the frontal lobe (e.g., Diamond, 2002; Luria, 1973; Wolfe & Bell, 2007; which is likely to play a major role in dual representations), rather than the need of social experience, that is responsible for the relatively late emergence of intentional action. And even if social experience does play a role, it may be the inability to distinguish between oneself and others, rather than dual representation that prevents an earlier onset of intentional action. Finally, the fact that action-effect acquisition and expectancy-based action has been observed in rats (Meck, 1985; Trapold, 1970), pigeons (Uricuioli & DeMarse, 1996), and cats (Brogden, 1962) does not suggest that complex experiences are necessary to develop these abilities, which among other things leaves the possibility that a certain degree of time-consuming exploration is required to build up the database of contingencies that ideomotor theory claims to be necessary for intentional action control. In any case, more research on the functional reasons underlying the qualitative step in intentional action control around 9 months of age is needed.

PREDICTIVE CODING

Ideomotor learning accounts for how a developing agent is increasingly able to intentionally select actions by considering and anticipating the effects they are expected to produce, but it does not address the agent's ability to experience agency and ownership. It has been argued that perceiving agency requires a comparison between predicted and actual effect of an action, the idea being that the agency experience is stronger the more similar the actual is to the predicted effect (Chambon & Haggard, 2013; Frith, Blakemore, & Wolpert, 2000; Tsakiris, Hesse, Boyd, Haggard, & Fink, 2007) as sketched in the right part of Figure 1. Combining the ideomotor and the predictive-coding aspect of voluntary action control suggests that action-effect associations are involved in two different action-control processes (Verschoor et al., 2013). For one, they translate representations of the intended effects into suitable actions: the anticipation of the intended effect activates the respective effect representation, which then spreads activation to the associated motor pattern. This process can be considered to perform *action selection*. For another, action-effect associations are used to predict the perceptual outcome of an action which, according to the predictive-coding approach, is compared to the actual action effect (e.g., Cardoso-Leite, Mamassian, Schütz-Bosbach, & Waszak, 2010; Hughes, Desantis, & Waszak, 2013a; for a review, see Hughes, Desantis, & Waszak, 2013b). Discrepancies signal an error (Band et al., 2009; Redgrave & Gurney, 2006) and a sufficient match will trigger the feeling of agency (Hommel, 2015). This process can thus be considered to perform *action evaluation*.[2]

Systematic research and theorizing on the interface between action selection and action evaluation is lacking, but there are reasons to assume that the two processes interact rather heavily. For instance, it has been shown that perceived agency over perceptual effects, irrespective of their valence, is in itself rewarding (Eitam et al., 2013; Karsh & Eitam, 2015). This might be taken to suggest that perceived agency informs the integration of action and effect representations, which would fit with the idea that phasic activity of ventral midbrain dopaminergic neurons might be responsible for reinforcing new action outcomes, again irrespective of their current valence (Redgrave & Gurney, 2006). However, the study of Elsner and Hommel (2004) suggests a different scenario. These authors compared the impact of contingency and contiguity between actions and effects on action-effect learning and perceived agency. While both measures were equally affected by the contingency and contiguity manipulations, they did not correlate. This does not fit with the assumption that perceived agency may determine whether action ef-

2. At a conceptual level our model takes an approach similar to action control as forward- and inverse-models of motor control (e.g., Gallagher, 2000; Wolpert & Kawato, 1998). In such models, forward modeling is akin to the action evaluation part of the model while inverse modeling covers the action-selection part. However, the emphasis of control models is commonly on the forward-modeling part while the informational basis underlying the inverse modeling part often remains underspecified. Considering the integration of bidirectional associations, we would argue, provides a natural database for inverse modeling to operate on. Hence, we agree with Chambon and Haggard (2013) that ideomotor theorizing and control theorizing need not be considered as competing but, rather, as both contributing to a comprehensive understanding of action control.

fects are integrated with their respective actions. Rather, it suggests a scenario in which ideomotor learning and agency perception share an informational resource, presumably the comparison between predicted and actual action effects (Hommel, 2015).

Another reason to assume that action selection and action evaluation interact but are not too tightly connected refers to the developmental dynamics. As we have mentioned earlier, there is evidence that action prediction precedes action selection: 7-month-olds are surprised by irregular action effects that they do not yet seem to be able to intentionally produce (Verschoor et al., 2013) and 6-month-olds can predict the goals of others (e.g., Biro & Leslie, 2007; Kamewari et al., 2005; Woodward, 1999). Given the evidence that successful use of expected action effects for the selection of intentional action emerges no earlier than around 9 months of age, this suggests that the ability to predict action outcomes develops faster or earlier than the ability to intentionally produce these action outcomes. In other words, action evaluation matures before action selection.

THE DEVELOPMENT OF AGENCY AND OWNERSHIP: CONCLUDING CONSIDERATIONS

The key argument that the present contribution aims to make is that selfhood is not a given but an achievement that agents construct through active interaction with their physical and social environment. The knowledge that such an active self integrates refers to contingencies between movements and outcomes that are used to select actions that are most likely to realize intended effects and to test predicted against actual outcomes. The very young age of the participants in the studies we have considered, and in particular their limited communicative abilities, did not permit us to directly assess their phenomenal agency and ownership experiences. But even if assessing such experiences would be possible, the quality of the experience is unlikely to match that of adults. Research on explicit agency and ownership judgments suggests that these kinds of judgments do not rely on single informational sources, such as the discrepancy between expected and actual effects but, rather, on a complex interplay between bottom-up information (Botvinick & Cohen, 1998) and top-down expectancies and considerations (Ma & Hommel, 2015a; Synofzik, Vosgerau, & Newen, 2008). For instance, adults tend to accept artificial virtual events as belonging to their body if only the behavior of these events is synchronous with their own movements (Ma & Hommel, 2015a) but there are also general ownership biases toward events that are more plausible body extensions in terms of shape or spatial location (Ma & Hommel, 2015a, 2015b). Given that adults are likely to have more experience and as more specific expectations than infants with regard to what may count as a plausible extension, the resulting judgments are likely to differ between these two populations.

Moreover, even in adults it is not quite clear whether and to what degree agency and ownership rely on different informational sources. While experiments using the rather artificial rubber hand illusion have sometimes suggested that ownership and agency are dissociable, more recent studies with more natural virtual-reality techniques suggest that ownership and agency judgments strongly correlate (Ma & Hommel, 2015a). Hence, it may well be that under ecologically valid conditions the experience of agency and the experience of ownership fall together and are no longer dissociable. However, it has also been argued that the perception of agency may mainly rely on exteroceptive sensory information, such as visible, proprioceptive or auditory action effects (Blanke, 2012; Blanke, Slater, & Serino, 2015; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Tsakiris, Hesse, Boyd, Haggard, & Fink, 2007), while the perception of ownership may require the integration of these sources with interoceptive information (Suzuki, Garfinkel, Critchley, & Seth, 2013; Tajadura-Jimenez, & Tsakiris, in press). If so, perceiving ownership may represent a more complex cognitive achievement than perceiving agency does, which in turn may delay its developmental onset and/or dynamics.

These considerations suggest that agency may be experienced before ownership. Note that the lack of ownership perception can be considered to support observational and imitative learning. Both functional frameworks like the theory of event coding (Hommel et al., 2001) and the mirror-neuron approach (e.g., Fabbri-Destro & Rizzolatti, 2008) have claimed that people are able to represent other people's actions just like their own actions, which logically presupposes the ability to "overlook" actual ownership. This implies a representational format ubiquitous to who owns the represented action. Interestingly, there is evidence that adults keep the ability to ignore ownership in some situations, which in turn increases the tendency to confuse their own attributes and actions with those of others (Ma, Sellaro, Lippelt, & Hommel, 2016). It is not unreasonable to speculate that infants start by not making that distinction in the first place, especially at a time where they strongly benefit from learning from others, and only slowly acquire the ability to assign ownership to actions. And it may be this ability that eventually completes the construction of a "self" (Baldwin, 1897; Burrow, 1927; Leont'ev, 1978; Mead, 1934; Vygotsky, 1962).

A particularly interesting implication of such a developmental scenario would be that it provides reason to abandon the production (action)-first (Cannon, Woodward, Gredebäck, von Hofsten, & Turek, 2012; Longo & Bertenthal, 2006; Melzer, Prinz, & Daum, 2012; Sommerville, Woodward, & Needham, 2005) versus perception-first (Biro & Leslie, 2007; Daum, Vuori, Prinz, & Aschersleben, 2009; Gergely, Nádasdy, Csibra, & Biro, 1995; Hofer, Hauf, & Aschersleben, 2005; Hofstadter & Reznick, 1996) debate in developmental psychology in favor of a contingency-first view that is agent-nonspecific and would not suggest any primacy of either production or perception. An interesting implication of this view with regard to the function of mirror neurons suggests that pre-motor areas (implicated in action mirroring) start out as a kind of generalized secondary motion processor associating any movement with its subsequent effects. In a subsequent developmental step, the ability to represent action in a bidirectional fashion emerges and exerts increasing impact on action control.

Taken altogether, we argue that there is increasing evidence that the phenomenal, minimal self is empirically derived from sensorimotor experience and not a theoretical and empirical given—self-by-doing so to speak. We have discussed evidence for a particularly important transition in the development of voluntary action control around the 9th month of age and suggested that the ability to predict the outcomes of one's actions developmentally precedes the ability to make active use of representations of these outcomes in producing goal-directed actions. It is through the development of these two functions that an active self eventually emerges.

REFERENCES

Amsterdam, B. (1972). Mirror self-image reactions before age two. *Developmental Psychobiology, 5*, 297-305.

Band, G. P. H., Van Steenbergen, H., Ridderinkhof, K. R., Falkenstein, M., & Hommel, B. (2009). Action-effect negativity: Irrelevant action effects are monitored like relevant feedback. *Biological Psychology, 82*, 211-218.

Baldwin, J. M. (1892). Origin of volition in childhood. *Science, 20*, 286-288.

Baldwin, J. M. (1897). *Social and ethical interpretations in mental development: A study in social psychology.* New York: Macmillan.

Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual Review of Psychology, 47*, 431-459.

Bertenthal, B., & Clifton, R. K. (1998). Perception and action. In D. K. W. Damon & R. Siegler (Eds.), *Handbook of child psychology: Vol. 2. Cognition, perception and language* (pp. 51-102). New York: Wiley.

Biro, S., & Leslie, A. M. (2007). Infants' perception of goal-directed actions: Development through cue-based bootstrapping. *Developmental Science, 10*, 379-398.

Biro, S., Verschoor, S. A., Coalter, E., & Leslie, A. M. (2014). Outcome producing potential influences twelve-month-olds' interpretation of a novel action as goal-directed. *Infant Behavior and Development, 37*, 729-738.

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience, 13*, 556-571.

Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron, 88*, 145-166.

Botvinick, M., & Cohen, J. (1998). Rubber hands "feel" touch that eyes see. *Nature, 391*, 756.

Brogden, W. J. (1962). Contiguous conditioning. *Journal of Experimental Psychology, 64*, 172-176.

Bruner, J. (1973). Organization of early skilled action. *Child Development, 44*, 1-11.

Burrow, T. (1927). *The social basis of consciousness.* New York: Harcourt, Brace.

Butterworth, G., & Hopkins, B. (1988). Hand-mouth coordination in the new-born baby. *British Journal of Developmental Psychology, 6*, 303-314.

Call, J., & Tomasello, M. (2008). Does the chimpanzee have a theory of mind? 30 years later. *Trends in Cognitive Sciences, 12*, 187-192.

Cannon, E. N., Woodward, A. L., Gredebäck, G., von Hofsten, C., & Turek, C. (2012). Action production influences 12-month-old infants' attention to others' actions. *Developmental Science, 15*, 35-42.

Cardoso-Leite, P., Mamassian, P., Schütz-Bosbach, S., & Waszak, F. (2010). A new look at sensory attenuation: Action-effect anticipation affects sensitivity, not response bias. *Psychological Science, 21*, 1740-1745.

Chambon V., & Haggard, P. (2013). Premotor or ideomotor: How does the experience of action come about? In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action science: Foundations of an emerging discipline* (pp. 359-380). Cambridge, MA: MIT Press.

Claxton, L. J., Keen, R., & McCarty, M. E. (2003). Evidence of motor planning in infant reaching behavior. *Psychological Science, 14*, 354-356.

Clearfield, M. W., & Thelen, E. (2001). Stability and flexibility in the acquisition of skilled movement. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (pp. 253-266). Cambridge, MA: MIT Press.

Courage, M. L., Edison, S. C., & Howe, M. L. (2004). Variability in the early development of visual self-recognition. *Infant Behavior and Development, 27*, 509-532.

Daum, M. M., Vuori, M. T., Prinz, W., & Aschersleben, G. (2009). Inferring the size of a goal object from an actor's grasping movement in 6- and 9-month-old infants. *Developmental Science, 12*, 854-862.

DeCasper, A. J., & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mothers' voices. *Science, 1208*, 1174-1176.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466-503). London: Oxford University Press.

Dutzi, I. B., & Hommel, B. (2009). The microgenesis of action-effect binding. *Psychological Research, 73*, 425-435.

Eenshuistra, R. M., Weidema, M. A., & Hommel, B. (2004). Development of the acquisition and control of action-effect associations. *Acta Psychologica, 115*, 185-209.

Eitam, B., Kennedy, P. M., & Higgins, T. E. (2013). Motivation from control. *Experimental Brain Research, 229*, 475-484.

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychology, 124*, 44-59.

Elsner, B., & Aschersleben, G. (2003). Do I get what you get? Learning about the effects of self-performed and observed actions in infancy. *Consciousness and Cognition, 12*, 732-751.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 229-240.

Elsner, B., & Hommel, B. (2004). Contiguity and contingency in the acquisition of action effects. *Psychological Research, 68*, 138-154.

Elsner, B., Hommel, B., Mentschel, C., Drzezga, A., Prinz, W., Conrad, B., & Siebner, H. (2002). Linking actions and their perceivable consequences in the human brain. *Neuroimage, 17*, 364-372.

Fabbri-Destro, M., & Rizzolatti, G. (2008). Mirror neurons and mirror systems in monkeys and humans. *Physiology, 23*, 171-179.

Field, T. M. (1979). Differential behavioral and cardiac responses of 3-month-old infants to a mirror and a peer. *Infant Behavior and Development, 2*, 179-184.

Fisher, C. B., & Lerner, R. M. (2005). *Encyclopedia of applied developmental science* (Vols. 1-2). Thousand Oaks, CA: Sage.

Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 355*, 1771-1788.

Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences, 4*, 14-21.

Gallup, G. G., Jr. (1970). Chimpanzees: Self-recognition. *Science, 167*, 86-87.

Gallup, G.G. Jr (1998). Self-awareness and the evolution of social intelligence. *Behavioural Processes, 42*, 239–247.

Gallup, G. G., Jr., Platek, S. M., & Spaulding, K. N. (2014). The nature of visual self-recognition revisited. *Trends in Cognitive Sciences, 18*, 57-58.

Gergely, G., Nádasdy, Z., Csibra, G., & Biro, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*, 165-193.

Gergely, G., & Watson, J. S. (1999). Early social-emotional development: Contingency perception and the socialbiofeedback model. In P. Rochat (Ed.), *Early social cognition* (pp. 101-136). Hillsdale, NJ: Erlbaum.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review, 77*, 73-99.

Harless, E. (1861). Der Apparat des Willens. *Zeitschrift fuer Philosophie und philosophische Kritik, 38*, 50-73.

Hauf, P. (2007). Infant's perception and production of intentional actions. In C. von Hofsten & K. Rosander (Eds.), *Progress in Brain Research: From Action to Cognition, 164*, 285-301.

Hauf, P., & Aschersleben, G. (2008). Action-effect anticipation in infant action control. *Psychological Research, 72*, 203-210.

Hauf, P., Aschersleben, G., & Prinz, W. (2007). Baby do–baby see! How action production influences action perception in infants. *Cognitive Development, 22*, 16-32.

Hofer, T., Hauf, P., & Aschersleben, G. (2005). Infant's perception of goal-directed actions performed by a mechanical device. *Infant Behavior and Development, 28*, 466-480.

Hofstadter, M., & Reznick, J. S. (1996). Response modality affects human infant delayed-response performance. *Child Development, 67*, 646-658.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59*, 176-186.

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research, 73*, 512-526.

Hommel, B. (2015). Action control and the sense of agency. In P. Haggard & B. Eitam (Eds.), *The sense of agency* (pp. 307-326). New York: Oxford University Press.

Hommel, B., & Elsner, B. (2009). Acquisition, representation, and control of action. In E. Morsella, J. A. Bargh, & P. M. Gollwitzer (Eds.), *The psychology of action* (pp. 371-398). New York: Oxford University Press.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding: A framework for perception and action planning. *Behavioral and Brain Sciences, 24*, 849-937.

Hughes, G., Desantis, A., & Waszak, F. (2013a). Attenuation of auditory N1 results from identity-specific action-effect prediction. *European Journal of Neuroscience, 37*, 1152-1158.

Hughes, G., Desantis, A., & Waszak, F. (2013b). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction and motor prediction. *Psychological Bulletin, 139*, 133-151.

James, W. (1890). *The principles of psychology*. New York: Dover.

Jones, S. S. (2009). The development of imitation in infancy. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*, 2325-2335.

Jovanovic, B., Király, I., Elsner, B., Gergely, G., Prinz, W., & Aschersleben, G. (2007). The role of effects for infants' perception of action goals. *Psychologia, 50*, 273-290.

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience, 6*, 40.

Kamewari, K., Kato, M., Kanda, T., Ishiguro, H., & Hiraki, K. (2005). Six-and-a-half-month-old children positively attribute goals to human action and to humanoid-robot motion. *Cognitive Development, 20*, 303-320.

Karsh, N., & Eitam, B. (2015). I control therefore I do: Judgments of agency influence action selection. *Cognition, 138*, 122-131.

Kenward, B. (2010). 10-month-olds visually anticipate an outcome contingent on their own action. *Infancy, 15*, 337-361.

Király, I., Jovanovic, B., Prinz, W., Aschersleben, G., & Gergely, G. (2003). The early origins of goal attribution in infancy. *Consciousness and Cognition, 12*, 752-769.

Klein, A., Hauf, P., & Aschersleben, G. (2006). The role of action effects in 12-month olds' action control: A comparison of televised model and live model. *Infant Behavior and Development, 29*, 535-544.

Kray, J., Eenshuistra, R., Kerstner, H., Weidema, M., & Hommel, B. (2006). Language and action control: The acquisition of action goals in early childhood. *Psychological Science, 17*, 737-741.

Kühn, S., Keizer, A., Rombouts, S. A. R. B., & Hommel, B. (2011). The functional and neural mechanism of action preparation: Roles of EBA and FFA in voluntary action control. *Journal of Cognitive Neuroscience, 23*, 214-220.

Leont'ev, A. N. (1978). *Activity, consciousness, and personality*. Englewood Cliffs, NJ: Prentice-Hall.

Longo, M. R., & Bertenthal, B. I. (2006). Common coding of observations and execution of action in 9-month-old infants. *Infancy, 10*, 43-59.

Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition, 107*, 978-998.

Lotze, R. H. (1852). *Medicinische Psychologie oder die Physiologie der Seele.* Leipzig: Weidmann'sche Buchhandlung.

Luria, A. R. (1973). The frontal lobes and the regulation of behavior. In K. H. Pribram (Ed.), *Psychophysiology of the frontal lobes* (pp. 3-26). Oxford, UK: Academic Press.

Ma, K., & Hommel, B. (2015a). Body-ownership for actively operated non-corporeal objects. *Consciousness and Cognition, 36,* 75-86.

Ma, K., & Hommel, B. (2015b). The role of agency for perceived ownership in the virtual hand illusion. *Consciousness and Cognition, 36,* 277-288.

Ma, K., Sellaro, R., Lippelt, D. P., & Hommel, B. (2016). Mood migration: How enfacing a smile makes you happier. *Cognition, 151,* 52-62.

Mead, G. H. (1934). *Mind, self and society: From the standpoint of a social behaviourist.* Chicago: University of Chicago Press.

Meck, W. H. (1985). Postreinforcement signal processing. *Journal of Experimental Psychology: Animal Behavior Processes, 11,* 52-70.

Melcher, T., Weidema, M., Eenshuistra, R. M., Hommel, B., & Gruber, O. (2008). The neural substrate of the ideomotor principle: An event-related fMRI analysis. *Neuroimage, 39,* 1274-1288.

Meltzoff, A. N. (2007). The "like me" framework for recognizing and becoming an intentional agent. *Acta Psychologica, 124,* 26-43.

Meltzoff, A. N., & Moore, M. K. (1977). Imitation of facial and manual gestures by human neonates. *Science, 198,* 75-78.

Meltzoff, A. N., & Moore, M. K. (1983). Newborn infants imitate adult facial gestures. *Child Development, 54,* 702-709.

Meltzoff, A. N., & Moore, M. K. (1997). Explaining facial imitation: A theoretical model. *Early Development and Parenting, 6,* 179-192.

Meltzoff, A. N., & Prinz, W. (Eds.). (2002). *The imitative mind: Development, evolution and brain bases.* Cambridge, UK: Cambridge University Press.

Melzer, A., Prinz, W., & Daum, M. M. (2012). Production and perception of contralateral reaching: A close link by 12 months of age. *Infant Behavior and Development, 35,* 570-579.

Nyström, P. (2008). The infant mirror neuron system studied with high density EEG. *Social Neuroscience, 3,* 334-347.

Nyström, P., Ljunghammar, T., Rosander, K., & von Hofsten, C. (2011). Using mu rhythm desynchronization to measure mirror neuron activity in infants. *Developmental Science, 14,* 327-335.

Papoušek, H., & Papoušek, M. (1974). Mirror image and self-recognition in young human infants: I. A new method of experimental analysis. *Developmental Psychobiology, 7,* 149-157.

Paulus, M., Hunnius, S., & Bekkering, H. (2013). Neurocognitive mechanisms subserving social learning in infancy: Infants' neural processing of the effects of others' actions. *Social Cognitive and Affective Neuroscience, 8,* 774-779.

Paulus, M., Hunnius, S., van Elk, M., & Bekkering, H. (2012). How learning to shake a rattle affects 8-month-old infants' perception of the rattle's sound: Electrophysiological evidence for action-effect binding in infancy. *Developmental Cognitive Neuroscience, 2,* 90-96.

Piaget, J. (1936). *The origins of intelligence in children.* New York: Norton.

Piaget, J. (1952). *The origins of intelligence in the child.* New York: Norton.

Povinelli, D. J., Landau, K. R., & Perilloux, H. K. (1996). Self-recognition in young children using delayed versus live feedback: Evidence of a developmental asynchrony. *Child Development, 67,* 1540-1554.

Premack, D., & Woodruff, G. (1978). Does the chimpanzee have a theory of mind? *Behavioral and Brain Sciences, 1,* 515-526.

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167-201). Berlin: Springer.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9,* 129-154.

Prinz, W. (2012). *Open minds: The social making of agency and intentionality.* Cambridge, MA: MIT Press.

Prior, H., Schwarz, A., & Güntürkün, O. (2008). Mirror-induced behavior in the magpie (Pica pica): Evidence of self-recognition. *PLoS Biology, 6,* 202.

Reddy, V., Chisholm, V., Forrester, D., Conforti, M., & Maniatopoulou, D. (2007). Facing the perfect contingency: Interactions with the self at 2 and 3 months. *Infant Behavior and Development, 30*, 195-212.

Redgrave, P., & Gurney, K. (2006). The short-latency dopamine signal: A role in discovering novel actions? *Nature Reviews Neuroscience, 7*, 967-975.

Renes, R. A., Vermeulen, L., Kahn, R. S., Aarts, H., & van Haren, N. E. (2013). Abnormalities in the establishment of feeling of self-agency in schizophrenia. *Schizophrenia Research, 143*, 50-54.

Rizzolatti, G., & Craighero, L. (2004). The mirror neuron system. *Annual Review Neuroscience, 27*, 169-192.

Rochat, P. (2001). *The infant's world*. Cambridge, MA: Harvard University Press.

Rochat, P., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements by 3- to 5-month-old infants. *Developmental Psychology, 31*, 626-636.

Rochat, P., & Striano, T. (1999). Emerging self-exploration by 2-month-old infants. *Developmental Science, 2*, 206-218.

Rovee, C. K., & Rovee, D. T. (1969). Conjugate reinforcement of infant exploratory behavior. *Journal of Experimental Child Psychology, 8*, 33-39.

Rovee-Collier, C. (1999). The development of infant memory. *Current Directions in Psychological Science, 8*, 80-85.

Sommerville, J. A., & Woodward, A. L. (2005a). Infants' sensitivity to the causal features of means-end support sequences in action and perception. *Infancy, 8*, 119-145.

Sommerville, J. A., & Woodward, A. L. (2005b). Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition, 95*, 1-30.

Sommerville, J. A., Woodward, A. L. & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition, 96*, B1-B11.

Stapel, J. C., van Wijk, I. C., Bekkering, H., & Hunnius, S. (2016). Eighteen-month-old infants show distinct electrophysiological responses to their own faces. *Developmental Science*. [Epub: August 22, 2016] doi: 10.1111/desc.12437

Suzuki, K., Garfinkel, S. N., Critchley, H. D., & Seth, A. K. (2013). Multisensory integration across interoceptive and exteroceptive domains modulates self-experience in the rubber-hand illusion. *Neuropsychologia, 51*, 2909-2917.

Synofzik, M., Their, P., Leube, D. T., Schlotterbeck, P., & Lindner, A. (2010). Misattributions of agency in schizophrenia are based on imprecise predictions about the sensory consequences of one's actions. *Brain, 133*, 262-271.

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition, 17*, 219-239.

Tajadura-Jimenez, A., & Tsakiris, M. (in press). Balancing the "inner" and the "outer" self: Interoceptive sensitivity modulates self-other boundaries. *Journal of Experimental Psychology: General*.

Au: Updates?

Traphold, M. A. (1970). Are expectancies based upon different reinforcing events discriminably different? *Learning and Motivation, 1*, 129-140.

Tsakiris, M., Hesse, M. D., Boyd, C., Haggard, P., & Fink, G. R. (2007). Neural signatures of body ownership: A sensory network for bodily self-consciousness. *Cerebral Cortex, 17*, 2235-2244.

Tsakiris, M., Schütz-Bosbach, S., & Gallagher, S. (2007). On agency and body-ownership: Phenomenological and neurocognitive reflections. *Consciousness and Cognition, 16*, 645-660.

Urcuioli, P. J., & DeMarse, T. (1996). Associative processes in differential outcome discriminations. *Journal of Experimental Psychology: Animal Behavior Processes, 22*, 192-204.

Verschoor, S. A., Eenshuistra, R., Kray, J., Biro, S., & Hommel, B. (2011). Explicit learning of arbitrary and non-arbitrary action-effect relations in adults and 4-year-olds. *Frontiers in Psychology, 2*, 354.

Verschoor, S. A., Spapé, M., Biro, S., & Hommel, B. (2013). From outcome prediction to action selection: Developmental change in the role of action-effect bindings. *Developmental Science, 16*, 801-814.

Verschoor, S. A., Weidema, M., Biro, S., & Hommel, B. (2010). Where do action goals come from? Evidence for spontaneous action-effect binding in infants. *Frontiers in Cognition, 1*, 201.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences, 8*, 266-272.

Vygotsky, L. S. (1962). *Thought and language*. (E. Hanfmann & G. Vakar, Trans.). Cambridge, MA: MIT Press.

Wang, Q., Bolhuis, J., Rothkopf, C. A, Kolling, T., Knopf, M., & Triesch, J. (2012). Infants in control: Rapid anticipation of action outcomes in a gaze-contingent paradigm. *PLoS ONE, 7*(2).

Watson, J. S. (1967). Memory and "contingency analysis" in infant learning. *Merrill-Palmer Quarterly, 13*, 55-76.

White, R. W. (1959). Motivation reconsidered: The concept of competence. *Psychological Review, 66*, 297-333.

Willatts, P. (1999). Development of means-end behavior in young infants: Pulling a support to retrieve a distant object. *Developmental Psychology, 35*, 651-666.

Wolfe, C. D., & Bell, M. A. (2007). The integration of cognition and emotion during infancy and early childhood: Regulatory processes associated with the development of working memory. *Brain and Cognition, 65*, 3-13.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural networks, 11*, 1317-1329.

Woodward, A. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition, 69*, 1-34.

Woodward, A. (1999). Infants' ability to distinguish between purposeful and non-purposeful behaviors. *Infant Behavior and Development, 22*(2), 145-160.

Woodward, A., & Sommerville, J. A. (2000). Twelve-month-old infants interpret action in context. *Psychological Science, 11*(1), 73-77.

Woodward, A. L., Sommerville, J. A., Gerson, S., Henderson, A. M. E., & Buresh, J. (2009). The emergence of intention attribution in infancy. *Psychology of Learning and Motivation, 51*, 187-222.

Zelazo, P. D. (1996). Towards a characterization of minimal consciousness. *New Ideas in Psychology, 14*, 63-80.

Zelazo, P. R., Brody, L. B., & Chaika, H. (1984). Neonatal habituation and dishabituation of headturning to rattle sounds. *Infant Behavior and Development, 7*, 311-321.