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Advances in understanding the perception-production link: Evidence from infant eye, brain, and motor behavior

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ABSTRACT

Empirical work has sparked notable progress in our understanding of how infants perceive and encode other people's actions, goals, and intentions. The role that infant action experience may play in this process – the perception-production link – has been a significant focus. Here, we analyze and unite three lines of work on this topic that have emerged over the last 25 years. First, looking-time measures have been used to assess whether infants' processing of others' goals is correlated with their own competence at performing similar actions. Second, studies have been designed to compare infants with different motor abilities and to intervene to alter infants' production experience, in order to test the effects of this experience on infants' subsequent perception of actions. Third, cognitive neuroscience techniques have been used to probe the neural correlates of infants' perception and production of actions by measuring the sensorimotor mu rhythm. We conclude with a look toward the future, including the value of investigating whether and how experience gained through action production contributes to and enriches action perception, and the promise of new infant brain-imaging techniques for addressing these enduring questions.

1. Introduction

Contemporary theories of human development—including theories as diverse as dynamic systems (Spencer et al., 2011), interactive specialization (Johnson, 2001), and developmental cascades (Masten & Cicchetti, 2010)—all emphasize that new abilities are not acquired in isolation from one another. Human development in different domains does not proceed autonomously; rather, changes in one domain influence development in others (Arterberry & Bornstein, 2024). Action processing is one area in which there is evidence for this developmental intertwining. Findings suggest that infants' learning to do new things with their own bodies helps them to visually recognize, interpret, and predict other people's actions. Detecting and using correspondences between the actions of self and other is proposed to be foundational for social-cognitive development (Meltzoff, 2007).

By the year 2000, imitation across the first two years of life had been widely studied. This research showed that infants use their perception of other people's actions to generate their own corresponding actions, and suggested a revision of Piaget's stage theory,

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which had depicted infant cognitive development as largely independent of the social world (Meltzoff, 2002; Rogers, 2006). Around this time, a burgeoning sub-field began using looking time to measure infants' processing of other people's actions. Using these measures, evidence rapidly accumulated showing that infants could perceive and encode others' actions and goals, without sophisticated mentalistic reasoning (e.g., Gergely & Csibra, 2003; Woodward, et al., 2001).

During the same time that these behavioral findings were emerging, discoveries in neuroscience were changing traditional views. The discovery of mirror neurons in non-human primates – neurons in premotor cortex that respond with a similar firing pattern to observed and performed actions – led to the suggestion that the neural substrates of the motor system may be more important for perception, communication, and social cognition than previously thought (Gallese et al., 2004; Rizzolatti & Craighero, 2004). Although many of the far-ranging hypotheses about the role of mirror neurons in human cognition have come under deserved scrutiny (Cook et al., 2014; Heyes & Catmur, 2022), the influence of these findings on the field of infant action processing is evident (e.g., Fox et al., 2016).

In the last 25 years, considerable progress has been made on investigating whether infants use their own experience to recognize and interpret other people's actions and goals. The literature encompasses behavioral studies of action anticipation and goal detection as well as cognitive neuroscience approaches examining activation of neural sensorimotor systems during observation of actions. In this review, we focus mainly on studies examining the perception-production link, encompassing diverse viewpoints and findings about how action experience may change or enrich action perception, and whether it exerts a causal effect.

2. Links between action perception and production

2.1. Perception of action

Looking-time measures are a crucial methodology in infant studies (Aslin, 2007). As used to investigate action perception, these measures include: (a) identifying whether infants can make an anticipatory look to the target of an action (Hunnius & Bekkering, 2010), (b) the latency of such looks (Adam et al., 2016; Cannon et al., 2012; Falck-Ytter et al., 2006; Melzer et al., 2012), (c) the relative duration of looking time to expected versus unexpected action outcomes (Daum et al., 2008, 2009, 2011), (d) habituation and novelty preference paradigms (Woodward, 2003), and (e) matching physical or socio-emotional effects to actions (Elsner & Aschersleben, 2003; Hauf et al., 2004; Ruba et al., 2019; Skerry & Spelke, 2014). Some investigators have debated what inferences can be drawn from looking behavior and raised questions about young infants' volitional control over eye movements (Blumberg & Adolphs, 2023; Canfield & Kirkham, 2001). Nonetheless, looking time is one of the primary measures used to investigate infant action processing. We synthesize these influential findings while noting interpretive caveats.

Key perception-production studies using the habituation/novelty preference approach derive from Woodward and colleagues (2001, 2003). They habituated infants to an actor reaching for a specific target object, then measured looking time to scenes in which the actor either: (a) reached to a new object in the old location or (b) reached to the old object in a new location. Results showed significantly more dishabituation to option-a than to option-b, suggesting that young infants encode the actor's goal and treat the switch of the goal-of-the-reach as more salient than a switch of location-of-the-reach (Woodward et al., 2009). There are, however, questions about what drives habituation, and the degree to which such measures reflect high-level cognitive processes or might be more compatible with leaner interpretations (Poli et al., 2024; Sirois & Mareschal, 2002). Beyond looking behavior, event-related potentials (ERPs) in infant electroencephalography (EEG) recordings have revealed differences in infants' neural activity while watching expected versus unexpected (or atypical) actions (Bakker et al., 2015; Reid et al., 2009).

2.2. Production of action

Developmental studies of the perception-production link are historically grounded in research on locomotion (Adolph et al., 2003), manual actions (Corbetta et al., 2000), and tool use (Lockman, 2000). The production side of the perception-production link has been conceptualized and measured in a wide variety of ways, which has been a source of some confusion in the field, because the results vary depending on the measure used. Across studies, measures have included: (a) the number or proportion of trials in which an infant successfully completed a motor action (e.g. Cannon et al., 2012; Melzer et al., 2012), (b) infants' speed in performing an action (e.g. Cannon et al., 2012), (c) assessments of qualities like how well-planned an action was (e.g. Sommerville & Woodward, 2005), and (d) a combination of multiple indices of behavior quality including parental report (e.g. Bakker et al., 2015; Stapel et al., 2016). We use the phrase "competence" to reflect the range of measures described in this list, which refers to the level of accomplishment tapped by these quantitative aspects of action performance.

Other measures of production include what we call "experience" in motor production, which refers to: (a) a measure of chronological experience (length-of-time) with a specific action (e.g. months of crawling, van Elk et al., 2008), (b) binary yes/no coding of whether or not the infant has any motor experience of a specific action (e.g. Gerson et al., 2015; Sommerville et al., 2005) or has achieved a specific motor milestone (e.g. Daum et al., 2011), or (c) empirical measures of production experience like the number of steps taken on a treadmill during an experiment (de Klerk et al., 2015a). In the remainder of this section, we focus predominantly on work correlating motor performance and perceptual processing using the competence measures defined above.

2.3. Associations between production competence and action perception

From at least 12 months of age, infants make anticipatory looks to the target of an adult's action, for example towards a container into which an actor is placing toys (Falck-Ytter et al., 2006). Cannon et al. (2012) used this paradigm to explore the perception-production link. They gave infants the opportunity to place toys in a container before or after watching an actor do so. Among infants who did the production task *before* the perception task, there was a positive correlation between their own success at putting toys in the container and how early infants looked to the target in the perception task. This finding indicates a potential connection between performing and anticipating the same action goal. If motor competence drives action perception, one would expect to see a consistent perception-production correlation. However, a correlation was not found in the perception-first group. An interpretation of this order effect is that recent performance may prime action representations. Under this interpretation, the correlation between looking behavior and competence during performance occurs because infants who completed more actions during this priming phase necessarily received more information about successful goal-directed actions.

Another procedure used to explore the perception-production link involves cross-body reaching, which infants do not perform reliably until about 6 months of age (van Hof et al., 2002). Melzer et al. (2012) found that the proportion of action production trials in which 12-month-olds' reached across the midline of their own body was correlated with how early they looked to the target of an actor's contralateral reach, suggesting that infants who more readily performed contralateral actions could better anticipate when another person's target involved crossing the body's midline.

Habituation paradigms have also been used to examine action processing. Having found that 12-month-old infants encode sequential actions as steps to achieving an overarching goal (Woodward & Sommerville, 2000), the authors examined the same process in 10-month-olds (Sommerville & Woodward, 2005). These infants were given the opportunity to perform the multi-step action of pulling a cloth to retrieve a toy sitting on it. Individual 10-month-olds who were better at retrieving the toy planfully (i.e., quickly pulling the cloth with visual fixation on the toy) also showed evidence of encoding another person's goal-directed, cloth-pulling action. These infants looked longer (dishabituated) at an adult pulling a cloth to retrieve a toy when the adult switched which object she was retrieving versus which cloth she was pulling. The ability of an infant to plan a specific multi-step action – one form of action competence – may therefore be correlated with that infant's encoding of the same action plan when performed by another person.

Moving from looking behavior to neuroscience measures, the P400 ERP is known to be responsive to socially-referential actions like gaze (Senju et al., 2006) and pointing (Gredebäck et al., 2010; Melinder et al., 2015). Bakker et al. (2015) found that the P400 was sensitive to whether a grasping hand was oriented towards or away from an object in 6-month-olds but not 4-month-olds. To probe whether variations in production experience might account for this, the authors also subdivided a sample of 5-month-olds based on grasping ability (combined lab-measured behaviors and parental report). The 5-month-olds with higher grasping scores showed a significant P400 difference for object-directed versus non-directed reaching. A second set of hand stimuli oriented towards or away from an object was shown to 6-month-olds, this time in a precision grip posture. No differences in the P400 response were found, a result attributed to 6-month-olds' lesser experience of precision than power grasping (though no productive precision grip measure was taken from this sample). Overall, these results suggest the potential roles of both experience and competence in infants' action encoding.

2.4. *Interim summary*

Taken together, despite differences in the specific measure of perception and production employed, the foregoing studies indicate that infants can anticipate the goals of others' actions by at least 12 months of age and that greater competence in producing these actions is associated with greater anticipation of the goals of others who are performing these same actions. However, the correlational nature of most of the foregoing work means that it does not establish a causal link between production and perception.

3. Effects of new action experience on perception

When an infant learns to perform an action, adding it to their motor repertoire, they have developed a motor program for that action or skill (hereafter called a "motor representation"). This representation may include the action goal. Once a skill is present, the corresponding motor representation could, in principle, be activated while infants watch someone else perform the same or a similar action. Comparisons between infants who differ on motor milestone attainment have therefore been used to explore the effects of action production on action perception.

One important infant motor milestone is the precision grip, in which an object can be grasped between the thumb and one or more fingers. In the earlier-emerging whole-hand or power grip, the digits are used to press an object against the palm. Daum and colleagues (2008) showed 6-month-olds a video of a hand with a wide or narrow grip shape reaching behind an occluder, followed by two images of the hand holding: (a) the outer cylindrical wall of a cup in a wide grip, and (b) the cup handle in a narrow grip. Infants looked longer at the final grasping image that did not match the original shape of the reaching hand. However, when a group of 6-month-olds was sorted into two sub-groups based on grasping ability, only those who could use precision-like thumb opposition looked significantly longer at the unexpected grip, suggesting a role for this motor milestone in processing others' actions (Daum et al., 2011). Loucks and Sommerville (2012) found a similar relation between ability to perform a precision grip and action perception in 10-month-olds. Infants who could use a precision grip to retrieve an object from a small box were sensitive to whether an actor's use of precision grip or a whole hand grip matched a target object they were reaching for.

Walking is another salient motor milestone. Stapel et al. (2016) found that 18- and 30-month-olds could anticipate the reappearance of crawling and walking toddlers from behind an occluder, but a group of 14-month-olds (inferred to have little walking experience) only accurately predicted crawlers' reappearance. In the same study, parent-reported months of walking experience and lab-measured walking competence (a combined measure of speed, step width, and path straightness) were taken from the

18-month-old sample. Neither the parent-reported nor lab-based walking measures related to action perception. These findings suggest that in the case of walking, it is attaining this milestone (and not the level of competence reached) that is associated with encoding other people's walking actions.

By focusing on specific motor skills that the infants do, or do not, have in their repertoire, the foregoing studies were able to examine whether perception is influenced by production. One caveat is that the experience gained upon attaining a new skill encompasses more than a motor representation. It may provide knowledge about causal action structure (e.g. Skerry et al., 2013). In the case of manual actions, it could also provide increased visual experience as a result of watching one's own performance. Moreover, even if we assume that learning to use a precision grip, or to walk, provides infants with a motor representation of those skills to use during action processing, it is often challenging to identify the exact onset of motor milestones. One-off motor production measures may misclassify infants, for example if they can perform a specific skill but it is not elicited in the lab. There is also a need to disentangle the effects of different aspects of production, including the distinction made earlier between competence level and raw experience.

3.1. Examining causal relations

Experimental manipulations can be designed to provide infants with experience of an action they have not yet performed. The sticky mittens paradigm provides infants presumed too young for consistent voluntary reaching and grasping with direct experience of picking up objects (Needham et al., 2002). Mittens with Velcro palms are put on the infants' hands, which allows the hand to adhere to toys, enabling a pick-up action. Sommerville et al. (2005) found that sticky mittens experience made 3-month-old infants more likely to encode an actor's goal (measured in a visual habituation paradigm), leading to the inference that experience of producing specific actions influences perception and understanding of such actions.

A recent review documented that an effect of sticky mittens experience on social perception – including action perception – has been found across multiple studies (van den Berg & Gredebäck, 2021). The review authors note, however, that the effect does not unambiguously implicate motor experience. They report mixed findings about whether training with sticky mittens enhances infants' reaching behavior when the mittens are not being worn. After a re-analysis of sticky mittens data, Liu and Almeida (2023) suggest that clear goals and salient effects caused by the action drive the effects of sticky mittens training on action processing more than first-person motor experience does. Another issue with a pure motor experience explanation is that when infants gain experience with reaching and grasping actions, they also see their own performance more often. Gerson and Woodward (2014a, 2014b) attempted to account for the role of visual experience by comparing 3-month-old infants who were given active sticky mittens experience to those who simply observed an actor with sticky mittens picking up objects. In the subsequent visual habituation test, only the infants who had received active training showed evidence of encoding an actor's reaching goal. The authors conclude that the effects of production on perception are not purely related to an increased visual exposure to a reach-and-grasp event.

Among the non-motor explanations of the sticky mittens effect described by van den Berg and Gredebäck (2021) are those related to the teleological stance (Gergely & Csibra, 2003), which holds that infants can access aspects of goal-directed action including efficiency and rationality in the absence of specific active experience. Skerry et al. (2013) gave 3-month-old infants sticky mittens experience, in which their reaches followed one trajectory, and then habituated them to an actor reaching along a different trajectory. During the subsequent visual test phase, these infants looked significantly longer at an inefficient than an efficient action. The authors suggest that sticky mittens effects derive from goal-related knowledge which may be fleshed out by successful reaching experience but is not due to recruitment of motor representations. Further, Woo et al. (2024) reported that pre-reaching infants are agnostic about whether action goals pertain to objects or locations. They suggest that sticky mittens training directs infants to expect the goal of a reach to be an object, rather than teaching them about goals generally. Relatedly, Gerson and Woodward (2014a) found that the effect of sticky mittens training transferred only to objects with which the infant had interacted.

Taken together, the range of findings from sticky mittens and motor milestone paradigms suggests that production experience influences action perception, but that the underlying process is not necessarily mediated by the activation of a motor representation in the perception task. The role of infants' self-experience in processing others' actions has also been examined through experimental training studies beyond the sticky mittens paradigm. The results are compatible with non-motor explanations of how infants can leverage self-experience to aid interpretation of other people's goal-directed behaviors (Meltzoff & Brooks, 2008).

4. Neural Mu rhythm measures of how action experience affects action processing

A newer body of research has probed the perception-production link by recording sensorimotor activity from the infant brain during specific tasks. This approach has advanced rapidly, and there is now an established literature on the activation of neural processes during infants' observation of others' actions, including theory-based review papers (Cuevas et al., 2014; Fox et al., 2016; Marshall & Meltzoff, 2011, 2014). The activation of neural processes during action observation is typically measured as desynchronization of the mu rhythm of infant EEG. Mu desynchronization has been reported in infants from 6 months of age while observing goal-directed actions (e.g. Filippi et al., 2016; Nyström, 2008; Nyström et al., 2011; Southgate et al., 2010).

Results indicate that mu desynchronization is stronger in response to goal-directed than non-goal-directed action (Nyström et al., 2011) and takes place even if the final state of the action is predictable but not visible (Southgate et al., 2010). Mu desynchronization cannot therefore be reduced simply to a response to movement, but is thought to tap something about the goal-directed nature of observed events. Several studies reported common patterns of neural activation during infants' observation of goal-directed actions by others and motor production of that action themselves (e.g., Marshall et al., 2011; Southgate et al., 2009). This work has generally been interpreted as suggesting shared neural networks for the observation and execution of manual actions. In human infants, the precise commonalities between the neural representations tapped by observation and execution warrant further study (Heyes & Catmur, 2022; Marshall & Meltzoff, 2014).

Mu desynchronization research, like behavioral research, has examined manual actions and locomotion (e.g. van Elk et al., 2008). Associations have been found between motor experience and mu desynchronization. Fourteen- to 16-month-old infants showed greater mu and beta desynchronization in response to videos of other infants crawling versus walking, with a greater difference in mu desynchronization for infants with longer experience of crawling (van Elk et al., 2008). This result suggests that there is a more significant neural response to observed action when infants have experience of performing that action. It should be noted that although access to a motor representation may influence processing of another's performance, this does not mean that motor competence with a specific action is *necessary* for mu desynchronization. de Klerk et al. (2016) found mu desynchronization in pre-walking 8-month-olds while they observed walking actions. Similarly, Meyer et al. (2016) found mu desynchronization in both 8- and 14-month-olds infants watching precision grips, despite none of the 8-month-olds performing a precision grip in the lab assessment.

Mu desynchronization was documented in 9- and 12-month-old infants when observing an adult either reaching for and grasping a toy or using a cane to pull the toy towards herself (Chung et al., 2022). Greater desynchronization for the reaching/grasping action was attributed to infants' greater experience with this action. Among the 9-month-olds alone, there was a positive association between individual infants' action competence in reaching for and grasping an object and the degree of mu desynchronization. In related work with 9- and 12-month-olds, Colomer et al. (2023) used a novel analytic approach to examine relations between visual alpha and mu oscillations. They used inter-site phase clustering to measure whether differences in oscillatory phase between occipital (visual) and central (sensorimotor) electrodes were consistent across action observation trials. Such consistency is taken as evidence of connectivity – the regions working together. Colomer et al.'s results showed greater visual-motor connectivity during action anticipation among 12-month-olds, relative to 9-month-olds. There was also an association between infants' own grasping competence and this visual-motor connectivity.

4.1. *Exploring causal links between action experience and neural measures*

Other neuroscience work provided infants with experimentally manipulated motor training. In one study, 7- to 9-month-olds infants, who had not yet learned to walk, were given experience of stepping on a treadmill while viewing a contingent video of their own legs or a non-contingent video of another infant's legs (de Klerk et al., 2015a). After this training, there was an increase in mu desynchronization to videos of other infants walking compared to baseline measures taken before the experience. There was no correlation between the strength of post-training mu desynchronization and the number of steps performed during training, suggesting that the increased response to others' actions was not due to motor experience alone. Among infants in the contingent condition, visual attention to the video during training predicted greater mu desynchronization, suggesting that experienced visuomotor contingency contributed to subsequent motor activation during observation.

Gerson et al. (2015) used a training paradigm to control for observational experience by giving 10-month-old infants self-experience with performing one new action, and observational-only experience of another action. Specific sounds were associated with each. After training, mu desynchronization was greater in response to the sound associated with the actively motor-trained action than to the sound associated with observational-only experience. Furthermore, only the response to the active-training sound, and not the observation-only sound, differed from a novel control sound. This finding suggests that experience of action performance enhances processing of the event beyond observational experience alone. However, Paulus et al. (2013) found significant mu desynchronization in 9-month-olds in response to a sound associated with a toy-shaking action that they merely observed someone else perform. This suggests that neural sensorimotor responses to sounds associated with actions can occur without active experience of producing that sound-action pairing. One possible explanation is that infants who cannot yet perform a specific motor skill (e.g. pincer grip, see Meyer et al., 2016) or who did not act on a specific toy (see Paulus et al., 2013) may nonetheless activate representations based on more general experience of accomplishing similar goal-directed actions (e.g. picking up or shaking an object; see also Southgate & Begus, 2013).

Neural sensorimotor activation has also been investigated via differences in the location of activation in response to actions using different parts of the body, reflecting the somatotopic organization of infant primary sensorimotor cortices. de Klerk et al. (2015b) reported that although motor execution of arm and leg actions in 12-month-olds resulted in somatotopic mu desynchronization, observation of both arm and leg actions was associated with arm areas only. Working with older infants (14-month-olds), Saby et al. (2013) reported that observing hand and foot goal-directed actions elicited somatotopic mu desynchronization in arm and foot areas respectively. The difference may reflect a developmental change, with 14-month-olds' greater locomotive experience enabling recruitment of the foot representation. Another explanation relates to paradigm differences. The action in the latter study was performed live, in-person, which has been shown to elicit a stronger mu response in infants than video-recorded actions as used in the former study (Ruysschaert et al., 2013; see also Cuevas et al., 2014). Either way, these studies illustrate the potential of a somatotopic approach to address questions about the perception-production link using specific parts of the body (Marshall & Meltzoff, 2015).

5. Future directions

Over the last 25 years, multiple methods have been used to investigate the development of a perception-production link. The findings do not support a strong view in which specific motor experience with an action is *necessary* for processing that action when performed by another. For example, infants without direct motor experience of goal-directed reaching can encode the target of an actor's reach (Woo et al., 2024). Infants without direct experience of walking or grasping already exhibit neural sensorimotor activation during observation (de Klerk et al., 2016; Meyer et al., 2016).

On the other hand, the view that motor experience exerts *no effect* on perception misses the full scope of the literature that has emerged over the last 25 years. Infants who can reach contralaterally, use a precision grip, or walk tend to visually anticipate others' performance of those actions better than age-matched infants without these skills (Daum et al., 2011; Melzer et al., 2012; Stapel et al., 2016). Furthermore, experimental interventions using sticky mittens are thought to show a causal effect of action experience on the perception of other people's goal-directed actions (Gerson & Woodward, 2014a, b; Sommerville et al., 2005). Moreover, prior motor experience is associated with neural sensorimotor activation while observing others' action performance (Gerson et al., 2015; van Elk et al., 2008).

One persistent issue noted in this review is the difficulty of disentangling the effects of visual or observational experience from active motor experience. Researchers have tried to do so by using training paradigms (Sommerville et al., 2005) and controlling for visual experience (Gerson et al., 2015; Gerson & Woodward, 2014a, 2014b). However, the effects could nonetheless be attributed to other goal-relevant information obtained through production, rather than to the motor experience per se (Skerry et al., 2013).

Where does that leave us in 2025? A new approach may be to test whether action processing is diminished if the execution of an action within the infant's motor repertoire is inhibited through an experimental intervention. This is the obverse of existing studies, such as sticky mittens approaches, which aim to train new action representations. Because neural interference methods like TMS are not feasible with infants, inhibition techniques could be adapted from the child and adult literature (Ambrosini et al., 2012; Sekiyama et al., 2014) in which, for example, a limb movement or specific manual grip type is blocked as the participant observes the action. Blocking approaches have been successfully used in related areas of infant research (Bruderer et al., 2015; Choi et al., 2021; Meltzoff & Brooks, 2008).

Another issue is the need to further explore why mu rhythm responses have been observed to actions the infant cannot (yet) perform (Meyer et al., 2016; Southgate & Begus, 2013). Comparing activation on the basis of the effector used in the action (hand versus foot) may reveal to what extent mu responses in infants represent *how* an act is being performed versus a more general goal like touching a target object. Harnessing the somatotopic organization of the infant brain holds promise for exploring perception-production links, but to date this approach has been used infrequently (de Klerk et al., 2015b; Marshall & Meltzoff, 2015; Saby et al., 2013). Future work can exploit more advanced neuroscience methods for finding patterns of activation, including EEG connectivity analysis, and improved source localization methods facilitated by infant-specific head models and templates (Colomer et al., 2023; Conte & Richards, 2022; Debnath et al., 2019; O'Reilly et al., 2021; Richards et al., 2016). The greater spatial sensitivity of infant magnetoencephalography (MEG) over EEG has been used to examine body representations in the infant brain (Meltzoff & Marshall, 2020). Infant MEG could now be used to study goal-directed actions performed with different body parts. There are rapid advances being made in infant MEG analysis (Bosseler et al., 2024; Clarke, Bosseler, et al., 2022; Clarke, Larson, et al., 2022) and in the development of optically-pumped MEG (Brookes et al., 2022; Orioli et al., 2025).

Another goal for future work is to create a more nuanced accounting of the development of the perception-production link over the course of infancy. To accomplish this, some conceptual and methodological groundwork remains to be done. As noted in this review, both production and perception have been measured in multiple ways by different researchers using different paradigms. This renders it difficult to interpret differences in outcomes. Much needed future progress about infant perception-production links is likely to come from large *N* longitudinal designs. In such designs, the same methods could be used to examine potential changes in action perception in individual infants over time, and how it is or is not influenced by motor development, increased action competence, and training on novel actions.

Over the last 25 years progress has been made by many researchers from multiple countries studying perception-production links. This work has illustrated the downstream effects of infant action production, and how it may affect infants' action prediction and processing as well as their neural sensorimotor responses to action. Advancing our understanding of the role of the perception-production link and how it contributes to other aspects of human development, such as social cognition, remains an enduring theoretical and practical issue as we look ahead to 2050.

CRediT authorship contribution statement

Andrew N. Meltzoff: Writing – original draft, Conceptualization. **Áine Ní Choisdealbha:** Writing – original draft, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors have no statements or disclosures to make regarding use of generative AI or declarations of interest. As this is a review paper, there are no declarations to make regarding data availability or the treatment of human subjects.

Declaration of Competing Interest

The authors have no competing interests to declare.

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Data Availability

No data was used for the research described in the article.

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