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The developing cognitive substrate of sequential action control in 9- to 12-month-olds: Evidence for concurrent activation models

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ABSTRACT

Nine-month-olds start to perform sequential actions. Yet, it remains largely unknown how they acquire and control such actions. We studied infants' sequential-action control by employing a novel gaze-contingent eye tracking paradigm. Infants experienced occulo-motor action sequences comprising two elementary actions. To contrast chaining, concurrent and integrated models of sequential-action control, we then selectively activated secondary actions to assess interactions with the primary actions. Behavioral and pupillometric results suggest 12-month-olds acquire sequential action without elaborate strategy through exploration. Furthermore, the inhibitory mechanisms ensuring ordered performance develop between 9 and 12 months of age, and are best captured by concurrent models.

1. Introduction

Infants are active, goal-directed agents (e.g., McCarty, Clifton, Ashmead, Lee, & Goubet, 2001). Interestingly, some of the actions they produce can be considered sequential, such as reaching for a rattle in order to shake it—a rather simple sequence, that comprises two dissociable components that differ in function and motor demands. Piaget (1936) and others (Claxton, Keen, & McCarty, 2003; Hauf, 2007; Willatts, 1999; Woodward & Sommerville, 2000; Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009) have stated that true goal-directed action emerges around 9 months of age when infants begin to be able to organize means-end action sequences in the service of overarching goals. Yet, the cognitive substrate of early sequential action control in infants remains completely uncharted territory. The purpose of the current study is to explore the cognitive mechanism sub-serving sequential action control in infants.

1.1. Development of action control in infancy

There are three prerequisites for infants to control sequential action: that they can represent actions, that they can represent sequential information and that they can combine those abilities to represent and control sequential action. Let us turn to the first prerequisite. There is ample evidence that actions are represented in terms of their effects. In his ideomotor theory, James (1890) states that actions are learned on the fly through sensorimotor exploration; an automatic mechanism creates bidirectional associations between perceived effects

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and the actions producing them (Hommel, 1996; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1990, 1997). These associations bring the actions under voluntary control, enabling the agent to activate the action by "thinking of" the corresponding effect. The theory can thus account for learning new actions and new goals.

This idea is typically tested in a two-stage paradigm. Experimenters first let subjects perform actions that lead to specific effects. After acquisition, they test if exogenously cueing an effect cues the action that previously caused it (Elsner & Hommel, 2001; Greenwald, 1970). This approach resulted in demonstrations of bidirectional action–effect acquisition for a wide range of actions and effects in children (Eenshuistra, Weidema, & Hommel, 2004; Kray, Eenshuistra, Kerstner, Weidema, & Hommel, 2006) and adults, suggesting the mechanism responsible to be fast-acting (Dutzi & Hommel, 2009), automatic (Band, van Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; Elsner & Hommel, 2001), implicit (Elsner & Hommel, 2001; Verschoor, Spapé, Biro, & Hommel, 2013), and modulated by the same factors that influence instrumental learning (Elsner & Hommel, 2004) (for a review on action–effect learning see: Hommel & Elsner, 2009). Furthermore, action–effects have also been found to be important for action evaluation (Band et al., 2009; Verschoor et al., 2013).

Until recently, research on the importance of action effects for infants mainly focused on third-person action interpretation (e.g., Biro & Leslie, 2007; Hauf, 2007; Kiraly, Jovanovic, Prinz, Aschersleben, & Gergely, 2003; Paulus, 2012; Paulus, Hunnius, & Bekkering, 2013; Woodward, 1998, for a review, see: Hauf, 2007; Kiraly et al., 2003) and imitation (Hauf & Aschersleben, 2008; Klein, Hauf, & Aschersleben, 2006; for a review see: Elsner, 2007; Paulus, 2014). Such findings are corroborative in view of the upsurge of theories stressing similar representations for first- and third-person action (e.g. Baker, Saxe, & Tenenbaum, 2009; Fabbri-Destro & Rizzolatti, 2008; Meltzoff, 2007; Tomasello, 1999). Interestingly, increased model- to self-similarity aids imitation (Shimpi, Akhtar, & Moore, 2013). Yet given their focus on action understanding, such studies tell us little about the function action effects have for the development of action control in infancy.

Direct evidence regarding action–effect learning was recently obtained from first-person paradigms similar to that of Elsner and Hommel (2001). Verschoor et al. (2013) showed that 7-month-olds use action effects for first-person action monitoring. By eight months, infants show motor resonance when listening to previously self-produced action-related sounds (Paulus, Hunnius, van Elk, & Bekkering, 2012). The youngest infants showing evidence for reversing bidirectional action effects for action control are 9-month-olds (Verschoor, Weidema, Biro, & Hommel, 2010). Comparable results were found in 12- (Verschoor et al., 2013), and 18-month-olds (Verschoor et al., 2010). Additionally 6-, 8- (Wang et al., 2012) and 10-month-olds (Kenward, 2010) anticipate action outcomes. Taken together these studies illustrate that 7-month-olds represent and monitor first- and third-person action in terms of action effects, while 9-month-olds additionally use action effects for action control.

1.2. Representing sequential information in infancy

Another prerequisite for representing sequential action is the ability to encode sequential information. Infants can register whether items are consistent with familiarized deterministic or probabilistic sequences (Romberg & Saffran, 2013). For instance, infants are susceptible to sequential grammar information in speech from birth (Gervain, Berent, & Werker, 2012; Teinonen, Fellmann, Näätänen, Alku, & Huotilainen, 2009), 3-month-olds are susceptible to spatiotemporal (Wentworth, Haith, & Hood, 2002) and audio–visual sequences (Lewkowicz, 2008) and 8-month-olds to analogous information in artificial sound (Marcus, Fernandes, & Johnson, 2007). Studies like these suggest an implicit, early-appearing, domain-general statistical information-acquisition mechanism for sequential information (e.g. Kim, Seitz, Feenstra, & Shams, 2009; Kirkham, Slemmer, & Johnson, 2002; Marcovitch & Lewkowicz, 2009) thought to sub-serve action- and language-segmentation (e.g. Baldwin, Andersson, Saffran, & Meyer, 2008; Saffran, Johnson, Aslin, & Newport, 1999). Nonetheless these studies leave open whether infants encode ordinal information among sequence elements. Indeed, Violation Of Expectation (VOE) research suggests that while 4-month-old infants encode statistical sequential properties, they cannot code the invariant order of sequences (Lewkowicz & Berent, 2009). This ability emerges during the second half of the first year (Brannon, 2002; Picozzi, de Hevia, Girelli, & Macchi-Cassia, 2010; Suanda, Tompson, & Brannon, 2008).

1.3. Sequential action representation in infancy

The reviewed literature shows that the first two prerequisites for infants' representation of sequential action emerge around 9 months. Yet, the question remains whether they can actually combine these abilities to represent and control action sequences. Indirect evidence comes from research that suggests infants are able to interpret third-person sequential actions. Evaluating such actions requires them to be parsed in order to perceive overall syntax and ultimately their goal (Baldwin, Baird, Saylor, & Clark, 2001; Conway & Christiansen, 2001; Lewkowicz, 2004). VOE studies report that around the age of 6 months infants start to evaluate the efficiency of sequential actions (Biro, Verschoor, & Coenen, 2011; Csibra, 2008; Gergely & Csibra, 2003; Verschoor & Biro, 2012) and causality towards their goals (Baillargeon, Graber, DeVos, & Black, 1990; Woodward & Sommerville, 2000). Olofson and Baldwin (2011) found that 10-month-olds take into account the kinematics of an observed reaching motion to judge whether it is part of a familiar action sequence. Yet, Paulus, Hunnius, and Bekkering (2011) showed that 20-, but not 14-month-old infants use such information to predict goals. Additionally, Gredebäck, Stasiewicz, Falck-Ytter, Rosander, and von Hofsten (2009) showed that 14- but not 10-month-olds' predictive eye movements are influenced by the models later intention with the object. Moreover, infants use social context to bind actions of two collaborating actors into action sequences for goal evaluation (Henderson, Wang, Matz, & Woodward, 2013;