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Infant motor and cognitive abilities and subsequent executive function

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ABSTRACT

Introduction: Although executive function (EF) is widely considered crucial to several aspects of life, the mechanisms underlying EF development remain largely unexplored, especially for infants. From a behavioral or neurodevelopmental perspective, motor and general cognitive abilities are linked with EF. EF development is a multistage process that starts with sensorimotor interactive behaviors, which become basic cognitive abilities and, in turn, mature EF.
Objectives: This study aims to examine how infant motor and general cognitive abilities are linked with their EF at 3 years of age. This work also aims to explore the potential processes of EF development from early movement.
Methods: A longitudinal study was conducted with 96 infants (55 girls and 41 boys). The infants' motor and general cognitive abilities were assessed at 1 and 2 years of age with Bayley Scales of Infant and Toddler Development, Second and Third Editions, respectively. Infants' EFs were assessed at 3 years of age with Working Memory Span task, Day–Night task, and Wrapped Gift task.
Results: Children with higher scores for cognitive ability at 2 years of age performed better in working memory, and children with higher scores for gross motor ability at 2 years performed better in cognitive inhibitory control (IC). Motor ability at 1 year and fine/gross motor ability at 2 years indirectly affected cognitive IC via general cognitive ability at 2 years and working memory.
Conclusions: EF development is a multistage process that originates from physical movement to simple cognitive function, and then to complex cognitive function. Infants and toddlers can undergo targeted motor training to promote EF development.

1. Introduction

Executive function (EF) is an umbrella term referring to higher-ordered and complex cognitive progresses needed for performing challenging goal-directed tasks. EF has three core elements: inhibitory control (IC), working memory (WM), and cognitive flexibility (CF) (Diamond, 2013; Piek et al., 2004; Willoughby, Blair, Wirth, & Greenberg, 2010). The considerable research attention devoted to EF is due to its important role in a child's school readiness and success, social interactions, and mental and physical health (Diamond,

Abbreviations: MA, motor ability; CA, cognitive ability; FM, fine motor ability; GM, gross motor ability; WM, working memory; C-IC, cognitive-inhibitory control; E-IC, emotional-inhibitory control

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2013). Although studies have established the relevance of EF to several aspects of life, the mechanisms underlying EF development remain largely underexplored. In view of the central role of frontal brain structures and the cerebellum in EF (Zelazo, Carlson, & Kesek, 2008), and of the close connection of brain development with early motor and general cognitive abilities (Diamond, 2000), the present study focuses on the relation between motor and general cognitive abilities during infancy, and on the subsequent EF.

Piaget's classic cognitive developmental theory posits that cognitive development relies on motor functioning (Siegler, Deloache, & Eisenberg, 2010). In addition, recent findings of both behavioral and neuroimaging studies suggest that motor performance is linked with higher-order cognitive processes (e.g., EF; Ridler et al., 2006; Rigoli, Piek, Kane, & Oosterlaan, 2012). At the behavioral level, the relation between motor performance and EF deficits is supported by studies on children with attention deficit hyperactivity disorder, developmental coordination disorder, and intellectual disabilities supported (Hartman, Houwen, Scherder, & Visscher, 2010; Sergeant, 2000; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Sergeant (2000) indicated that for atypical developing children, motor abilities and EF have several overlapping underlying processes; nonetheless, a few studies involving typical developing children found controversial results. A study involving five- to six-year-old children reported that motor ability and EF were unrelated except for one task for WM (Wassenberg et al., 2005). A recent study that also involved five- to six-year-old children found that motor skill performance was positively related to EF (Stöckel & Hughes, 2016). From current neurobiological perspective on their relationships, the executive control network, containing both parts of the prefrontal cortex and primary motor cortex, is one of the large scale networks comprised of distributed brain areas dynamically interacting with each other (Bressler & Menon, 2010; Menon & Uddin,2010). For example, the coordination of prefrontal and posterior parietal area is connected with the activity of sensory and motor areas (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008; Corbetta & Shulman, 2002; Ruff et al., 2006). Individual differences in EF emerge, in line with the rapid development of the brain and neural networks, during early childhood (Cao, Huang, & He, 2017; Garon, Bryson, & Smith, 2008). Unfortunately, few studies have specifically investigated the interrelations between infant motor abilities and EF. For example, Murray et al. (2006) reported an evidently linear correlation between age at learning to stand and adult EF. Another study focusing on WM found that earlier acquisition of the ability to walk was connected to better performance on WM in early old age (Poranen-Clark et al., 2015). Thus, the present study focuses on infants and examines whether relationships can be established between motor abilities at 1–2 years and EF at 3 years of age.

Basic cognitive abilities are closely related to EF among children, adolescents, and adults (Pangelinan et al., 2011; Salthouse, 2005). For example, preterm 11-year-olds exhibited a slower processing speed than their full-term peers; such preterm deficit may result in poor performance in all three core aspects of EF (Rose, Feldman, & Jankowski, 2011). Early-appearing cognitive abilities, including process speed, attention, memory, and representation competence (Rose, Feldman, & Jankowski, 2005), have long-term implications on EF. A longitudinal study by Rose et al. found that memory assessed in infancy and toddlerhood predicted the WM at 11 years old, and that early processing speed predicted the performance in shifting and WM at the age of 11 (Rose, Feldman, & Jankowski, 2012). Except for studies declaring that basic cognitive abilities were related to EF in terms of a few discrete abilities, only one study involving early childhood mentioned that general cognitive ability assessed by standardized measurement at 12 months old positively predicted WM at 18 months old and all EF elements at 26 months old (Bernier, Carlson, Bordeleau, & Carrire, 2010). However, Friedman et al. found that general cognitive ability was unrelated to all aspects of EF in adults (Friedman et al., 2006). According to Wass' (2015) review on studies that applied cognitive training targeted at early EF development, limited studies had successfully applied cognitive training to typically developing children in the age range of 0- to 5 years old. Thus, the relation between infant general cognitive ability and subsequent EF remains unknown.

According to embodied cognition, which is similar to the Sensorimotor Stage of Piaget's developmental theory, knowledge and representational ability are derived from sensorimotor interactions with the environment (Pezzulo, 2011). After investigating the role of the cerebellum in the control processes of motor behaviors and EF, Koziol, Budding and Chidekel (2012) declared that EF development is a multistage process. That is, EF begins from sensorimotor interactive behaviors, which develop into basic and bottom-up cognitive abilities and, in turn, generate the mature forms of EF (Koziol & Lutz, 2013). In addition, as we discussed above, several studies have proven that both motor and cognitive abilities are related to EF (e.g., Sergeant, 2000; Wilson et al., 2013). Other studies verify that motor ability is associated with cognitive development (Burns, O'Callaghan, McDonell, & Rogers, 2004; Piek, Dawson, Smith, & Gasson, 2008; Wijnroks & Veldhoven, 2003), in that motor ability may serve as a "control parameter" for future development, particularly during early life when infant motor behavior is crucial to the acquisition and practice of cognitive ability (Bushnell & Boudreau, 1993). Thus, the predictive effect of children's early motor abilities on subsequent EF can possibly be mediated by their cognitive abilities; however, few studies have explored this topic.

EF is widely considered a domain-general cognitive function, and various sub-functions are assumed to work together to realize goal-directed processes (Diamond, 2013). However, studies on the functions of the dorsolateral prefrontal cortex and the medial frontal and orbitofrontal areas suggest that EF operates differently in different contexts; thus, recent works have attempted to identify the distinction between the "cool" cognitive parts of EF and the "hot" emotional parts (Zelazo & Carlson, 2012). Cool EF refers to top-down control processes that are manifested under relatively decontextualized, nonemotional, and analytical testing conditions, such as WM, cognitive inhibitory control (IC), and cognitive flexibility. Hot EF refers to top-down control processes elicited in contexts involving emotion, motivation, and a tension between immediate gratification and long-term rewards, which often measured with tasks having emotional component (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Nigg, 2017; Peterson & Welsh, 2014). Many tasks are used to evaluate cool EF; whereas the newer concept of hot EF is probed by relatively small set of tasks, such as delay of gratification (Welsh & Peterson, 2014). In addition to being intertwined (Diamond, 2013), the relation between WM and IC changes with development (Roncadin, Pascual-Leone, Rich, & Dennis, 2007). Jacques and Marcovitch (2010) assumed that WM contributed to both cognitive and emotional IC, and this statement was supported by findings involving infants and preschoolers (Bernier et al.,