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Developmental improvements in reaching correction efficiency are associated with an increased ability to represent action mentally

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A B S T R A C T

We investigated the purported association between developmental changes in the efficiency of online reaching corrections and improved action representation. Younger children (6–7 years), older children (8–12 years), adolescents (13–17 years), and young adults (18–24 years) completed a double-step reaching paradigm and a motor imagery task. Results showed similar nonlinear performance improvements across both tasks, typified by substantial changes in efficiency after 6 or 7 years followed by incremental improvements. Regression showed that imagery ability significantly predicted reaching efficiency and that this association stayed constant across age. Findings provide the first empirical evidence that more efficient online control through development is predicted, partly, by improved action representation.

Introduction

Development of online control

The ability to correct one's movement mid-flight in response to unexpected environmental changes has received much attention in the literature of late (e.g., King, Oliveira, Contreras-Vidal, & Clark,

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2012; Ruddock et al., 2014; Wilson & Hyde, 2013). This so-called online control of movement is seen as a marker of the nervous system's capacity to interact effectively with an unpredictable and fluid environment, a critical feature of a mature motor system. Despite this, little is known about its development through childhood and beyond. The limited evidence that is available, however, suggests a nonlinear maturation. Specifically, during early childhood (prior to 8 years) mid-movement corrections to reaching following unexpected target perturbation are slow and highly variable. However, by mid-childhood (around 8 years), the efficiency with which a child can engage in these types of online corrective actions improves substantially. This period is followed by more subtle performance improvements into adolescence and beyond (King et al., 2012; Ruddock et al., 2014; Wilson & Hyde, 2013).

For example, Wilson and Hyde (2013) recently compared the performance of younger (6–7 years), mid-aged (8–9 years), and older (10–12 years) children, as well as young healthy adults, on the well-validated double-step reaching task (DSRT). Participants were required to reach for one of three targets presented on a touch screen. For most trials the target remained stationary for the duration of movement, whereas for the remaining trials the target jumped at movement onset (jump trials). During this task, non-jump trials are thought to place few demands on online corrective systems because the target remains stationary throughout movement. That is, presuming that the initially programmed motor command is accurate, it can unfold unchanged. Conversely, the unexpected target perturbation that occurs during jump trials renders the initial motor command inaccurate. As such, successful trial completion is dependent on how efficiently an individual can update the motor command in real time and, hence, facilitate the timely redirection of the limb toward the newly cued target. Consequently, immature or impaired online control manifests as poor performance on jump trials relative to non-jump, a profile shown by patient groups where deficits in the online control of movement are core symptoms, including parietal lesion patients (Blangero et al., 2008; Gréa et al., 2002; Ochipa et al., 1997). Interestingly, Wilson and Hyde (2013) showed that whereas jump trial reaching speed (relative to non-jump) was relatively slow during early childhood (6–7 years), it decreased substantially by middle childhood (8–9 years) and remained relatively stable into older childhood. This age-related improvement in accounting for target perturbation was confirmed by kinematic analyses that showed a significant reduction in time to reach trajectory correction values between younger and middle childhood, where they then stabilized into later childhood (i.e., 10–12 years). Importantly, this developmental profile of online control is a consistent feature of the small number of developmental studies into the online control of reaching (King et al., 2012; Ruddock et al., 2014).

From a computational perspective, the ability to engage in online reaching corrections is thought to depend heavily on an individual's ability to represent action at an internal neural level. Specifically, the nervous system is thought to use an efferent copy of the impending motor command to anticipate the limb trajectory should the movement unfold as anticipated. On movement initiation, actual visual and proprioceptive in-flow becomes available and is compared with the predicted sensory information (as per the action representation) in real time. In case of a mismatch (e.g., following unexpected target perturbation), an error signal is generated which must then be integrated seamlessly with the unfolding motor command, affording fluent and efficient correction to the moving limb (Desmurget & Grafton, 2000). By anticipating the sensory consequences of movement, this predictive modeling system allows the nervous system to circumvent sensory processing delays (which can exceed 250 ms; Frith, Blakemore, & Wolpert, 2000) with minimum lag (Desmurget & Grafton, 2000; Shadmehr, Smith, & Krakauer, 2010). In neural terms, this system appears to be supported by a functional loop between connections across motor and frontal cortices and parietal and cerebellar networks (Andersen & Cui, 2009; Izawa & Shadmehr, 2011; Mulliken, Musallam, & Andersen, 2008). This neurocomputational modeling is supported by a strong body of indirect (Hyde & Wilson, 2011a, 2011b; King et al., 2012; Ruddock et al., 2014; Wilson & Hyde, 2013) and direct (Hyde, Wilmut, Fuelscher, & Williams, 2013) empirical evidence demonstrating that the efficiency with which individuals are able to implement online control is dependent on their capacity to generate and integrate internal "neural" action representations with incoming sensory information. Accordingly, it is generally argued that the nonlinear improvement in online control observed between the critical years spanning ages 6 to 12 is subserved by an improved ability to generate and/or use internal "action" representations