Human Movement Science 32 (2013) 1138–1150

Contents lists available at SciVerse ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

The development of rapid online control in children aged 6–12 years: Reaching performance

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A R T I C L E   I N F O

Article history:
Available online 9 August 2013

PsycINFO classification:
3250

Keywords:
Motor control
Online control
Motor development
Predictive control
Feedforward
Feedback

A B S T R A C T

Rapid online control during reaching has an important bearing on movement accuracy and flexibility. It is surprising then that few studies have investigated the development of rapid online control in children. In this study, we were particularly interested in age-related changes in the nature of motor control in response to visual perturbation. We compared the performance of younger (6–7 years of age), mid-aged (8–9), and older (10–12) children, as well as healthy young adults using a double-step reaching task. Participants were required to make target-directed reaching movements in near space, while also responding to visual perturbations that occurred at movement onset for a small percentage of trials. Results showed that both the older and mid-aged children corrected their reaching in response to the unexpected shifts in target location significantly faster than younger children, manifest by reduced time to correction. In turn, the responses of adults were faster than older children in terms of movement time and on kinematic measures such as time to correction and time to peak velocity. These results indicate that the capacity to utilize forward estimates of limb position in the service of online control of early perturbations to ballistic (or rapid) reaching develops in a non-linear fashion, progressing rapidly between early and middle childhood, showing a degree of stability over mid and later childhood, but then evidence for continued refinement between childhood and young adulthood. The pattern of change after childhood and into early adolescence requires further investigation, particularly during the rapid phase of physical growth that accompanies puberty.

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http://dx.doi.org/10.1016/j.humov.2013.02.008

1. Introduction

Rapid online control is critical to our ability to move flexibly and efficiently in response to dynamic changes in the environment. It is surprising, therefore, that so little is known about the development of *rapid online control* in children and the processes that support it during goal-directed reaching. It is currently thought that this form of control depends on the motor system's ability to utilize predictive control—that is, to generate a predictive estimate of limb dynamics and to integrate this estimate (or forward model) in real time with sensory feedback (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Wolpert, Diedrichsen, & Flanagan, 2011). Data based largely on adults suggest that this process is subserved by fast visuomotor channels at the level of parieto-frontal cortex, and reciprocal links between parietal (particularly posterior) cortex and the cerebellum (Ferraina, Battaglia-Mayer, Genovesio, Archambault, & Caminiti, 2009; Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006). Specifically, whereas the PPC plays an important role in state-estimation and integrating visual feedback with predictive estimates of limb position (Buneo & Anderson, 2006), the cerebellum is involved in regulating the timing control between agonist and antagonist bursts in a predictive manner; as such, it is crucial to online processing using feedforward information (Salman, 2002). Indeed, in the case of the posterior parietal cortex, interruption through lesion or TMS has shown to result in a virtual inability to correct the reach trajectory in response to unexpected target perturbation (viz. online control) (Desmurget et al., 1999; Gréa et al., 2002). While (normative) neuroimaging data on children is lacking, there is evidence for greater coupling between parietal cortex and cerebellum with development, which likely subserves the observed transition in manual performance through mid-childhood (see below) (Johnson, 2011).

At the level of movement skill, we know that there is a gradual (though non-linear) increase in reaching proficiency from mid childhood (~5 years) into early adulthood (Bard, Hay, & Fleury, 1990; Chicoine, Lassonde, & Proteau, 1992). However, it is not entirely clear whether this change in performance is associated with better integration of feedforward- and feedback-based control, specifically the ability to use predictive control when adjusting movement to sudden changes in the environment. Using a visual perturbation paradigm, we examined this issue by comparing the ability of children aged 6–7 years, 8–9 years and 10–12 years and healthy young adults to enlist rapid online control.

The efficiency of rapid online control is an important marker of a mature and healthy motor system and is thought to be achieved by fast internal feedback loops (Izawa & Shadmehr, 2011; Wolpert et al., 2011). A predictive (forward) model uses a copy of the motor command (viz. efference copy) to predict the visual and somatosensory consequences of an impending action. In the event of unexpected perturbation (either visual or mechanical), a mismatch occurs between the predicted and actual sensory consequences of action. This results in an error signal that is used to modify the motor command in real time, with minimal lag. Indeed, adjustments of this kind can occur within 70–100 ms (Castiello, Paulignan, & Jeannerod, 1991; Farnè et al., 2003; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). By comparison, sensory processing alone can take upwards of 250 ms (see Frith, Blakemore, & Wolpert, 2000), by which time the limb has moved appreciably with respect to the target location. Thus, the integrity of this predictive modelling mechanism—also referred to as an internal feedback loop—helps ensure movement efficiency under dynamic environmental conditions.

1.1. The changing nature of (online) motor control over the course of child development

The development of predictive control has been demonstrated in a range of contexts that involve non-visually mediated responses including dynamic force control (Konczak, Osmann, & Kalveram, 2003), isometric (manual) force control (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003), and anticipatory postural adjustments (Hay & Redon, 1999). These studies suggest a shift in control strategies between the ages of 5 and 12 years characterized by more efficient integration of predictive and feedback-based mechanisms. For example, some now classic work investigating manual control