Available online at www.sciencedirect.com
ScienceDirect
Consciousness and Cognition 16 (2007) 886–896
Consciousness and Cognition
www.elsevier.com/locate/concog

Adolescent development of motor imagery in a visually guided pointing task

Suparna Choudhury [a,*], Tony Charman [a], Victoria Bird [a], Sarah-Jayne Blakemore [b]

[a] *Behavioural and Brain Sciences, Institute of Child Health, University College London, 30 Guilford Street, London WC1N 1EH, UK*
[b] *Institute of Cognitive Neuroscience, Department of Psychology, University College London, 17 Queen Square, London WC1N 3AR, UK*

Received 14 June 2006
Available online 29 December 2006

Abstract

The development of action representation during adolescence was investigated using a visually guided pointing motor task (VGPT) to test motor imagery. Forty adolescents (24 males; mean age 13.1 years) and 33 adults (15 males; mean age 27.5 years) were instructed to both execute and imagine hand movements from a starting point to a target of varying size. Reaction time (RT) was measured for both Execution (*E*) and Imagery (*I*) conditions. There is typically a close association between time taken to execute and image actions in adults because action execution and action simulation rely on overlapping neural circuitry. Further, representations of actions are governed by the same speed-accuracy trade-off as real actions, as expressed by Fitts' Law. In the current study, performance on the VGPT in both adolescents and adults conformed to Fitts' Law in *E* and *I* conditions. However, the strength of association between *E* and *I* significantly increased with age, reflecting a refinement in action representation between adolescence and adulthood.

Keywords: Adolescence; Motor imagery; Action representation; Cognitive development; Internal models; Action prediction; Simulation

1. Introduction

Motor imagery is a conscious, first-person simulation of an action. An example of a motor image is the imagined sensation of generating the force of the leg to kick a football, without actually moving. It is proposed that motor imagery of a specific action is based on the internal representation of intended but unexecuted actions (Jeannerod, 1997). As such, the conscious generation of a motor image reflects an unconscious internal action representation, or "internal model" of volitional movements (Jeannerod, 1997). It has been proposed that internal motor representations, also known as forward models, serve as predictors in the brain (Miall & Wolpert, 1996). Prediction is a necessary step in motor planning and can be used in many ways, for example, for fine motor adjustments, action planning and motor learning. For every intended action, the brain must issue a motor command to the muscles in order to execute the action. It is proposed that a duplicate of the

* Corresponding author. Fax: +44 20 7831 7050.
E-mail address: s.choudhury@ich.ucl.ac.uk (S. Choudhury).

1053-8100/$ - see front matter © 2007 Published by Elsevier Inc.
doi:10.1016/j.concog.2006.11.001

motor command—or 'efference copy'—is generated in parallel and used to make predictions about the sensory consequences of one's own action (Miall & Wolpert, 1996). Internal forward models are used, for example, to gauge the relationship between predicted states and desired states and to provide the motor instructions required by the muscles to achieve the desired effect, such as the grip force necessary to manipulate a given object (Wolpert, Ghahramani, & Jordan, 1995). Accurate motor control requires up to date information about the external world. For example, it is only possible to make accurate reaching movements by acquiring an internal model of our limb dynamics. Recently, Voss et al. have shown that internal model prediction occurs even in the absence of movement (Voss, Ingram, Haggard, & Wolpert, 2006).

A tight correlation between the timing of a specific action and its imagined equivalent has been shown to be a robust phenomenon, suggesting that actions in both modalities are subject to the same environmental and physiological constraints (Decety & Michel, 1989; Jeannerod, 1994; Sirigu et al., 1995; Wilson, Maruff, Ives, & Currie, 2001). For example, there is no difference in the time taken to carry out or to imagine tasks that involve writing, drawing (Decety & Michel, 1989), walking (Decety, Jeannerod, & Prablanc, 1989; Stevens et al., 2004), performing simple hand actions (Sirigu et al., 1996) or reaching to targets (Cerritelli, Maruff, Wilson, & Currie, 2000; Maruff, Wilson, Trebiolcock, & Currie, 1999; Wilson et al., 2001). Furthermore, the visually guided pointing task (VGPT), which involves object-directed actions, has previously been used to show that, typically, the duration of target-oriented reaching movements increases as the size of the target decreases (Cerritelli et al., 2000; Maruff et al., 1999), both when the actions are executed and imagined. In other words, task difficulty, also referred to as the index of difficulty, affects actions in the same way, regardless of modality. Taken together, the temporal invariance between real and imagined movements suggests that the same motor representation governs an action whether it is real or imagined.

This phenomenon can be expressed by Fitts' Law. This describes the logarithmic relationship between the speed and accuracy of real movements, and has been shown to extend to imagined movements in typical participants (Fitts, 1954). In other words, we make the same speed-accuracy trade-offs for both real and imagined actions. For example, for both real and imagined movements, we slow down in order to reach accurately to increasingly small targets, or we take longer to walk to increasingly distant targets (Decety et al., 1989; Maruff et al., 1999; Sirigu et al., 1996; Wilson et al., 2001). Imaging and lesion studies have suggested that the parietal cortex is involved in the imagination of actions (Gerardin et al., 2000; Lacourse, Orr, Cramer, & Cohen, 2005; Sirigu et al., 1995; Stephan et al., 1995). In addition it has been suggested that internal models are stored in parietal cortex (Blakemore & Sirigu, 2003).

The body is subject to considerable development during adolescence, including an increase in limb size. In order to maintain accurate motor control, internal models need to be updated in accordance with physical development during this transitional period. Although motor imagery is a well-established phenomenon in healthy adults, to our knowledge the development of this ability during adolescence has not previously been studied. In the current study, the VGPT was used to tap internal models in adolescents and adults, and mental chronometry was used as the measure of ability to represent actions. We compared the correspondence in timing between Executed and Imagined actions between adolescents and adults, as well as compliance to Fitts' Law. We predicted that there would be a main effect of Index of Difficulty (ID), with all participants taking a longer time to reach for the smaller targets (Cerritelli et al., 2000; Maruff et al., 1999; Sirigu et al., 1995, 1996; Wilson et al., 2001), due to the speed-accuracy trade off typically represented. Furthermore, given the pronounced development of body structure and therefore limb dynamics during adolescence, we hypothesised that forward modelling for action control would show parallel development. We predicted that this would be reflected by an increase between adolescence and adulthood in the correspondence between Execution and Imagery times.

2. Methods

2.1. Participants

Forty adolescents (24 males; mean age 13.1 years, $SD = 1.35$) and 33 adults (15 males; mean age 27.5 years, $SD = 7.91$) took part in the study. Adolescent participants were from secondary schools in the London area and adults were staff and students from University College London. All participants were from the central