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Age-related changes in motor imagery from early childhood to adulthood: Probing the internal representation of speed-accuracy trade-offs

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ABSTRACT

The purpose of this study was to chart the development of motor imagery ability between 5 and 29 years of age and its relationship to fine-motor skill. 237 participants performed a computerized Virtual Radial Fitts Task (VRFT) as a measure of Motor Imagery (MI) ability. Participants aimed at five targets, positioned along radial axes from a central target circle. The targets differed in width over trials (2.5, 5, 10, 20 or 40 mm). Performance was indexed by the relationship between the movement time (MT) in executed and imagined movements. A subset of participants (11–19 years old, $n = 22$) also performed the task with their non-preferred hand. We also examined if manual skill (measured by peg board task and posting coins) was related to the executed and imagined MT on the VRFT. Our results showed that the accuracy of the imagined movement improved steadily over childhood, reaching an asymptote during adolescence and into early adulthood. The correlation between the real and virtual MT using the preferred hand did not differ appreciably from that using the non-preferred hand. If the children could perform the tasks with their non-preferred hand (11 years and older), they also scaled performance in relatively precise terms using the less dextrous non-preferred hand. The correlation between real MT on the VRFT and fine-motor performance ranged between .53 and .42, while that for virtual movement was between .37 and .34. MI ability predicts manual skill to a moderate degree.

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1. Introduction

When making reaching movements to targets of different sizes healthy performers show remarkably similar movement profiles. These profiles are adapted to task constraints like required accuracy and are scaled in a manner that minimizes energy costs and endpoint variability. The very clear trade-off between speed and accuracy, also known as Fitts' Law (Fitts, 1954), has been described in many tasks and movement contexts, is already present in young children (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Smits-Engelsman, Sugden, & Duysens, 2006), and evident even in patient groups with brain damage (Caeyenberghs, van Roon, Swinnen, & Smits-Engelsman, 2009; Smits-Engelsman, Rameckers, & Duysens, 2007).

The ability to adjust movement characteristics to required accuracy constraints is widely thought to be an intrinsic property of the motor system, and more recently, thought to depend on predictive control (e.g., Bye & Neilson, 2008; Gawthrop, Lakie, & Loram, 2008). From a computational perspective, predictive control is a form of internal modeling that uses a predictor and a state estimator in order to regulate systems with long sensorimotor feedback delays. The cerebellum is thought to store internal models for action that enable the organism to predict the dynamic properties of the motor system (Imamizu, Kuroda, Yoshioka, & Kawato, 2004; Imamizu et al., 2000; Miall & Wolpert, 1996) and, hence, provide modeled feedback *before the actual sensory feedback has arrived* in the central components of the motor system. For this control system to work, an estimation of the state of the body in space is needed: this state estimator appears to involve parieto-cerebellar loops (Desmurget et al., 1999; Desmurget & Grafton, 2000). Here, a state estimation is computed from motor output signals, sensory input, and contextual information. Together, the cerebellum and the parietal cortex provide the feedforward flow of information needed for fast, 'online' corrections, minimizing the need for inherently delayed visuomotor feedback (Gréa et al., 2002; Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998). Any deficit in this process makes goal directed movements largely dependent on slower visual and re-afferent feedback as seen in young children.

Performance according to Fitts' law depends on contextual information (target size and distance to the target) as well as on evaluation of the proposed movement characteristics.

Adherence to Fitts' law presupposes an ability to predict the consequences of one's motor actions. This predictive function develops over time and may be less adequate in younger children (Molina, Tijus, & Jouen, 2008; Smits-Engelsman, Swinnen, & Duysens, 2006) and children with poor motor skill (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Gabbard & Bobbio, 2011; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Wilson, Thomas, & Maruff, 2002).

Motor imagery – the process by which an individual rehearses or simulates a given action – has gained attention in recent decades since it was shown to be (partly) represented in the same basic motor circuits as action execution (Jeannerod, 2003). Because motor imagery conforms to the same basic physical and environmental constraints as that governing real movement, it provides an alternative source of information about how well the outcome of a movement can be predicted (Decety & Jeannerod, 1995). For example, if the timing of an imagined movement does not change under different accuracy demands then it can be inferred that the performer does not have a clear internal model of their own movement dynamics; this has been demonstrated in younger children, for example. Further, we argue that in order to mentally reproduce an activity, the individual should have experience of performing that activity under similar (although not identical) external constraints. Clearly, varied movement experiences during the course of child development helps shape the (implicit) knowledge that the child acquires about the behavior of their own motor system; this supports the ability to predict or imagine how a movement should unfold given a particular set of physical constraints (like object size, location, and so on), as well as the ability to adjust movements in-flight should these predictions not match the dynamic state of the environment.

Our starting assumption, then, is that the ability to produce and monitor action representations is an important control parameter in the development of movement skill (Frith, Blakemore, & Wolpert, 2000). In support of this, we have shown in earlier work that the correlation between real and imagined action increases over the course of child development and, further, the relationship is much