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Abbreviations

AE	Anticipatory Error
AJE	Anti-jump Error
AMT _{diff}	Anti-jump Movement Time Difference
CTE	Centre Touch Error
DJRT	Double Jump Reaching Task
MT	Movement Time
MT _{diff}	Movement Time Difference
PCT	Post Correction Time
PFC	Prefrontal Cortex
PPC	Posterior Parietal Cortex
RT	Reaction Time
ToC	Time of Correction
ToC2	Second Time of Correction
TDE	Touch Down Error

Online control is part of a broader cognitive system that underlies action systems and is subject to changing constraints with childhood development.

The ability to rapidly and seamlessly adjust arm movements in response to sudden or unexpected changes in the environment (i.e. *online control*) is crucial to flexible and efficient action. Current neuro-computational modelling holds that this form of control is dependent on an individual's ability to generate a predictive model of an intended movement and integrate it 'on the fly' with sensory feedback throughout the movement cycle (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Wolpert, Diedrichsen, & Flanagan, 2011).. In essence, this mechanism allows the nervous system to circumvent delays associated with basic sensory feedback processing. That is, if incongruence between the estimated (according to the predictive model) and actual consequences of movement is detected, rapid corrective mechanisms can be implemented within 100ms (Castiello, Bennett, & Chambers, 1998; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991), far too quickly to be accommodated by sensory processing alone. Thus, a system of predictive control, also referred to as an *internal feedback loop*, is critical for movement stability under dynamic conditions. From a neural perspective, these systems appear to be supported by finely tuned reciprocal connections between parieto-cerebellar cortices and upstream motor areas (Shadmehr & Krakauer, 2008). Surprisingly, little is known of its development.

Efficient online correction of reaching is a key indicator of a functional and mature motor system. Developmentally, the motor system matures rapidly over childhood; however, the trajectory does not appear to be linear (for a review see Elliott, Chua, & Helsen, 2001). Our earlier work using a double-step perturbation suggests a somewhat different trajectory with rapid development of online control after early childhood (6-7 years) , and then similar levels of proficiency when mid-aged (8-9 years) and older (10-12 years) children are compared (Wilson & Hyde, 2013) Results showed that 5-7 year olds were significantly

slower to adjust their reaching to visual perturbation than either mid-aged or older children while the latter two groups did not differ. Interestingly, online corrections occurred somewhat earlier in adults, manifest by a more efficient trajectory on jump trials, a pattern not seen in children of any age. Hence, the fast internal feedback loops that support very early and rapid changes in trajectory may not fully mature until adolescence or early adulthood (Farnè et al., 2003).

To date, there is little direct neurophysiological data on rapid online control (and predictive modeling) in children. However, adult data suggests a pivotal role for the parietal cortex, especially the PPC, in the ongoing representation of body schema, the dynamic mapping of limb-to-target relations, and the real-time integration of feedforward commands with sensory feedback. For visually-guided reaching, the PPC is thought to play a crucial role in state estimation, continuously integrating dynamic visual inflow with predictive estimates of limb position, (Wolpert, Ghahramani, & Flanagan, 2001). and is also involved in processing the resultant error signal; for example, a spike in PPC activity occurs immediately after unexpected target displacement and is tuned to its direction (Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011). This signal would be transferred to frontal motor centres, modulating the motor command as it unfolds and modifies the flight path of the hand, so to speak, with minimal lag.

Importantly, recent morphological evidence indicates that the cortical structures involved in goal-directed action and predictive control (principally the fronto-parietal axis), follow a protracted period of development (Johnson, 2005). Motor and perceptual centres do mature earlier than higher-cortical areas associated with cognitive control, and the pattern of activation tends to shift from diffuse to more focal with age across childhood (Casey, Tottenham, Liston, & Durston, 2005). Importantly, the rapid improvement in online control we see after early childhood occurs after a period of rapid growth in white matter volume in

parietal and frontal cortices. This is followed by a period of neural sculpting during middle and later childhood; a combination of factors, both progressive (i.e. myelination) and regressive (e.g. synaptic pruning and/or grey matter loss) contribute to this, mediated by experience (Casey et al., 2005). A switch from diffuse to localised neural firing throughout this period play an important role in neuro-cognitive development broadly. This process is underpinned by continued white matter maturation but also experience driven synaptic pruning through childhood (and into adolescence), contributing to improvements in cognitive and motor skills (e.g. Barnea-Goraly et al., 2005)). These changes to pre-frontal cortices and their connectivity to other neo- and sub-cortical structures (e.g. visual pathways and cortico-thalamic and cortico-spinal tracts) support greater cognitive flexibility in children, and top-down modulation of what were previously more automatic processes in infants and young children. The ability to enlist inhibitory control in the face of compelling environmental cues is a case in point (Casey et al., 2005). We argue that prefrontal motor control processes that are supported by parieto-cerebellar pathways (e.g., rapid online control and motor adaptation) enable more behavioural flexibility under changing external conditions (Posner, Rothbart, & Sheese, 2007).

Interactive specialization: Implications for the interplay between online control and executive function

The notion of interactive specialization posits that some regions of the cortex, while unfolding at a relatively slow rate, can still modulate the activity of other areas, influencing the tenor of cognitive processing (Johnson, 2005). In other words, the emergence of a new behaviour is the result of weighted activity from several brain regions whose modular architecture and rate of maturation may differ in complexity and timescale. Neuronal regions are initially ill-defined and are enlisted in response to a broad range of stimuli. With time and experience, cortical regions become more specialised, and shift from diffuse to more focal

activation for a given class of stimuli (Durstun et al., 2006). Importantly, functional activity of a given cortical region is determined by how it is coupled to other regions and their modulating effect. New cognitive processes and behaviours thus arise as a result of changes to multiple regions rather than site-specific effects.

In the context of action, frontal systems, in particular, play an increasingly important role in the control of movement throughout development as environmental constraints become more complex or variable and demands on top-down control increase (Brocki & Bohlin, 2004). For example, increases in task complexity that occur when an individual is required to unexpectedly and rapidly adjust their reaching place demands on limited capacity working memory systems, subserved by a functional loop between the dorso-lateral prefrontal cortex and parietal cortex (Suchy, 2009). Moreover the degree of coupling between anterior and posterior regions increases over childhood (Casey, Getz, & Galvan, 2008). Taken together, it is possible that that ability to enlist online control of movement under more complex task constraints (e.g. when executive control demands are higher) may be limited in younger children to the extent that the modulating effect of frontal executive functions is less well coupled to posterior visual-motor centres.

Perhaps the most significant transition in the development of executive function occurs between 4 and 8 years where cognitive flexibility expands concomitant to continued myelination and synaptic pruning of the prefrontal cortex (PFC) and its reciprocal connections downstream (Casey et al., 2008; Johnson, 2005). What is particularly interesting is the fact that at a time when specialised frontal functions are unfolding during middle childhood (but not necessarily consolidated) we also see evidence of different solutions to online control; for example, greater reliance on feedback control under some circumstances (e.g. Chicoine, Lussonde, & Proteau, 1992). That said, we have little direct evidence to test the hypothesis that children of middle childhood perform goal-directed reaching much like

older children under simple task constraints, but may struggle when these constraints are heightened, enlisting greater frontal modulation.

Nonetheless, correlational data suggest a link between executive control and the development of movement skill, more generally. We know from behavioural studies that levels of inhibitory control (e.g., Stroop performance and initiation of anti-saccades) are correlated with movement skill in both younger (Livesey, Keen, Rouse, & White, 2006) and older (Piek, Dyck, Francis, & Conwell, 2007) children. Similarly, we see that problems of inhibition are common in children with poor motor skills (Mandich, Buckolz, & Polatajko, 2002; Wilmut, Brown, & Wann, 2007).

We suggest that the development of online control is likely to be constrained by the unfolding of fronto-executive systems. Hence, the aim of this study was to understand how executive control is enlisted in the context of movement that requires rapid online adjustments. Using a double-jump reaching task, we predicted that because mid-aged children are still developing a workable coupling between frontal and posterior (motor control) systems, they would show performance decrements under conditions of inhibitory load; this would result in slower online corrections, and a pattern of behaviour more akin to that observed in younger children.

Method

Participants

The sample was taken from a larger study in a longitudinal project. The sub-sample consisted of 129 children (56 boys and 73 girls) between the ages of 6 and 12 years. Three schools were randomly selected from the greater Melbourne area and metropolitan Perth regions. Children were divided into three age bands: young (6-7 years); mid-age (8-9 years); and older (10-12 years). Table 1 displays the descriptive data for age, gender, and handedness of each group. Parents completed a questionnaire to indicate if their child suffers from a

previously diagnosed intellectual/developmental/ learning disorder or serious medical condition (e.g. asthma, visual impairment, epilepsy, etc...), which was then corroborated by the child's classroom teacher. Five children were excluded from the study based on a previously diagnosed developmental disorder: one child reported motor control difficulties; one reported Autism Spectrum Disorder; one reported Dyslexia; and two reported Specific Language Impairment. No child reported intellectual disability; accordingly, since all children were recruited from mainstream primary schools, it was assumed that children included in the study were within normal IQ range (Hyde & Wilson, 2011a).

Materials

The Double-Jump Reaching Task (DJRT) paradigm was used to assess online motor control. The VIRTOOLS Software Package (3DVIA, 2010) was used to develop the computer interactive display on a black Samsung 40" touch screen television (refer to Figure 3 for experimental set-up). The television was placed on top of a table with its screen facing up and was raised at a 10° angle from horizontal and positioned in portrait view when a child performed the task. The background of the monitor screen was black to match the frame of the TV and reduce contrast while the participant performed the task. The display consisted of a green 'home base' circle 2.5cm in diameter and positioned 5cm from the edge of the display. Three yellow targets were situated above the home base in the middle of the screen. Target locations were positioned -20° , 0° , 20° from the direction of the home base target. To account for age-related differences in arm reaching, the distance to the yellow targets were scaled according to arm length (taken from Gerver, Drayer, & Schaafsma, 1989) across the three groups: young children, 25cm; mid-age children, 28cm; and older children, 30cm. Arm movement was captured using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis which sampled at 200Hz. It was placed one meter directly above the centre-point of the television. A small ultrasonic marker (7mm in diameter) was used to track arm

movement. The marker was connected by cord from the Zebris to the child's dominant index finger and held in place by an adhesive pad that was stuck to the tip of the index finger nail.

Procedure

Principals from three randomly selected primary schools around metropolitan Melbourne and three randomly selected schools in metropolitan Perth area were contacted and invited to participate in the study. Information about the study was sent home via letter with children at each school, outlining the nature of the research to parents. The study was approved by the Australian Catholic University Ethics Committee, Victorian Department of Education and Early Childhood Development, and the Melbourne Catholic Education Office. Informed consent was provided by each school principal and children were eligible to participate if their parent/guardian completed and returned an informed consent statement to the head researcher.

Hand preference was assessed using a two-step procedure: i) children were asked which hand they liked to write with and ii) children were handed a pen to write their name and observed which hand they used. All trials were performed using the dominant hand. To ensure the cord attached to the kinematic sensor on the child's index finger did not obscure hand movement and interfere with movement trajectory, the researcher secured cord slack away from the child. Before the commencement of the experiment, children were explained the nature of the task. The DJRT was performed in a quiet school classroom with low light to prevent visual feedback from the moving limb (Farnè et al., 2003). Children stood in front of the monitor and used their index finger to reach and touch the targets.

Two versions of the DJRT were administered during the testing session: a typical DJRT and an anti-jump DJRT. For the typical DJRT, the green 'home base' was first illuminated at the start of each trial. Children held their index finger stationary on this target until the 'home base' light was extinguished and a yellow target was simultaneously

illuminated: a random delay of 500-1500ms minimised anticipatory effects. To direct visual attention to the same place on each trial, children were instructed to reach and touch in the middle of the target as *quickly and accurately as possible* until the light was extinguished. A successful trial was indicated with an auditory tone when the centre of the correct newly acquired target was pressed. For the majority of trials (80%), the initially illuminated target remained stationary until it was pressed (*non-jump* trial). However, for a small percentage of trials (i.e. remaining 20% of trials) the target jumped to either of the peripheral target location after finger lift-off (*jump* trial) from the home base. During these ‘jump’ trials, children were instructed to also *follow and press the middle of the target as quickly and accurately as possible*. Upon completion of each trial, children were instructed to return their finger to home base ready to repeat the next trial.

During the anti-jump DJRT, children performed a modified version of the first DJRT: similarly to the earlier version, for most trials (80%) the target remained stationary for the duration of movement, yet for a small percentage of trials (20%) the target ‘jumped’ laterally at movement onset. During the latter condition, children were instructed to reach to the target on the opposite side of the illuminated target (see Figure 3.)

The order in which the two conditions were presented to children was randomised to account for potential learning effects. Within each condition, children were administered two blocks with each block contained 40 trials: 32 *non-jump* trials and 8 *jump/anti-jump* trials (four trials to the left and four to the right peripheral location). The sequence of trials was programmed into the task so that non-jump, jump, and anti-jump trials occurred pseudo-randomly. At the end of each testing block, children were permitted a two minute interval to rest.

Before the task commenced, a researcher demonstrated the action required for the 3 trials; *non-jump*, *jump*, and *anti-jump*. Children were then given 10 practice trials (8 *non-*

jump trials and 2 *jump/anti-jump* trials) to become familiar with the task. Where necessary, the researcher provided additional practice trials until he was satisfied that children understood the task.

Data Analysis

Chronometric measures taken were reaction time (RT), measured as the time between illumination of the central target and finger lift-off from 'home base', and movement time (MT), defined as the time taken between finger lift off from 'home base' to the moment the index finger successfully touched inside the yellow target. Only valid *non-jump*, *jump* and *anti-jump* trials (i.e. where a child successfully touched the centre of a yellow target) were included. Outliers were removed, defined as those values $> \pm 2.5$ SDs from the mean. An average of 19 (24%) *non-jump* trials and 2 (25%) *jump/anti-jump* trials were removed from the younger group, 18 (23%) and 2 (25%) respectively from the mid-age group, and 18 (23%) *non-jump* and 2 (25%) *jump/anti-jump* trials respectively from the older group. *Jump-* and *anti-jump* trials were collapsed over left and right target locations. Trials that incurred an error were removed from the data set. A criterion of 8 successful *jump/anti-jump* trials per block was set as a minimum requirement to include the data in the analysis. Mean RT and MT were then calculated for each child. Mean RTs were compared between age groups using 1-way ANOVA. The pattern of mean MT was compared between groups using 2-way repeated measures ANOVA (3[Group] x 2 [Trial Type: Jump & Anti-Jump]). Movement time difference scores were also calculated between the average MT for *non-jump* and *jump* trials (MT_{diff}) and then between *non-jump* and *anti-jump* trials (AMT_{diff}). Each difference score was compared between age groups using 1-way ANOVA.

In addition, three kinematic variables were recorded. Kinematic data (i.e. ToC, ToC2, and PCT) were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For *jump-* and *anti-jump* trials, time of correction (ToC) represented the first detectable

point at which the finger deviated from its straight movement path toward the centre yellow target when it changed direction toward a peripheral target (Hyde & Wilson, 2011b; Pisella et al., 2000; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007). Similarly to healthy adults who perform tasks that require inhibition of a prepotent response toward a cued stimulus, participants showed a tendency for the hand's 'automatic pilot' to initially reach toward the illuminated target on displacement trials of the 'anti-jump' DJRT, prior to re-directing their reach trajectory toward the opposite target location (Cameron, Cressman, Franks, & Chua, 2009). Hence, for anti-jump trials two ToC values (ToC and ToC2) were measured: the first trajectory correction away from the initial target to the illuminated target, and a second re-direction of the reach trajectory towards the opposite target location.

Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software where ToC and ToC2 values were independently determined by two researchers to ensure reliability. ToC was analysed using a 2-way repeated measures ANOVA (3[Group: younger x mid-age x older children] x 2 [Trial Type: Jump & Anti-Jump]) to assess for an interaction effect between groups on trials where an inhibitory load is present or not while ToC2 was analysed using 1-way ANOVA. In addition, post-correction time (PCT) was recorded from the initial point of movement correction on both jump and anti-jump trials to successful finger touchdown on the touchscreen. This was analysed using 2-way repeated measures ANOVA. Kinematic data (i.e. ToC/ ToC2 and PCT) were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For each dependent variable outliers were removed if they were deemed $-2.5 < \text{or} > 2.5 + SD$ from the mean score.

Four types of response errors were recorded for the DJRT: touch down error (TDE) occurred when children touched outside the boundaries of a yellow target; anticipatory error (AE) was recorded when lift-off from 'home base' occurred before the yellow central target was illuminated and/or when RT was less than 150ms (Wilson, Maruff, & McKenzie, 1997);

centre touch error (CTE) was defined as a touch to the central target instead of a peripheral target during a jump trial; and anti-jump error (AJE) occurred when children pressed the incorrect (or cued target) during an anti-jump trial. 1-way ANOVA was also used to assess the mean difference between groups on each error variable (TDE, AE, CTE, & AJE).

Preliminary analyses showed that site location and gender were not systematically related to performance on any measure. Measures of effect size (partial η^2) were used to interpret the magnitude of the effect.

Results

Reaction time

Overall, there was a significant age effect, $F(2,92) = 24.29, p < .001$, partial $\eta^2 = .35$: RTs for older children (462 ms) were faster than 8-9 year-olds (508 ms) who, in turn, were faster than 6-7 year-olds (575).

Movement time

The mean MT (+/- SE) for each group is displayed in Figure 1. The 2-way ANOVA on mean MT showed a significant main effect for trial type, Wilks' $\Lambda = .08, F(2,99) = 609.76, p < .001$, partial $\eta^2 = .93$, and age group, $F(2,100) = 18.52, p < .001$, partial $\eta^2 = .27$. The interaction between age group and trial type was also significant, Wilks' $\Lambda = .77, F(4,198) = 6.91, p < .001$, partial $\eta^2 = .12$.

Tests of simple effects showed no differences between the three age groups on non-jump trials. For jump trials, 6-7 year olds (837 ms) were significantly slower than both 8-9 year-olds (727 ms), $p < .001$, partial $\eta^2 = .15$, and 10-12 year-olds (681 ms), $p < .001$, partial $\eta^2 = .28$, while the two older groups were not shown to differ, $p = .23$, partial $\eta^2 = .07$. On anti-jump trials, younger children (1235 ms) were significantly slower than 8-9 (1080 ms), $p = .003$, partial $\eta^2 = .13$ and 10-12 year olds (984 ms), $p < .001$, partial $\eta^2 = .28$. The difference between the two older groups was not significant, $p = .079$, partial $\eta^2 = .10$.

Movement time difference

The average MT_{diff} score between non-jump trials and jump trials was calculated and compared between the groups. 1-way ANOVA revealed a significant effect for age group, $F(2,116) = 10.54, p < .001, \text{partial } \eta^2 = .15$. Post-hoc tests revealed that the MT_{diff} score for the youngest children (393 ms) was significantly longer than that for 8-9 year-olds (286 ms), $p = .002$, and 10-12 year-olds (253 ms), $p < .001$. The comparison between the two older groups was not significant, $p = .49$.

For the AMT_{diff} score between non-jump and anti-jump trials, 1-way ANOVA revealed a significant age group effect, $F(2,110) = 19.30, p < .001, \text{partial } \eta^2 = .26$. Follow-up tests revealed that the AMT_{diff} score of the youngest children (750 ms) was significantly greater than the 8-9 year-olds (611 ms), whose score, in turn, was greater than the 10-12 year-olds (524 ms), with each $p < .05$.

Time of Correction (ToC and ToC2)

The average ToC (+/- SE) for each group is displayed in Figure 2. The 2-way ANOVA on the mean ToC found no significant interaction between group and trial type, Wilks' $\Lambda = .99, F(2,98) = 0.34, p = .71, \text{partial } \eta^2 = .007$. Overall, children were faster to correct initial trajectory on standard jump trials (290 ms) than anti-jump trials (298 ms), Wilks' $\Lambda = .95, F(1,98) = 5.47, p = .021, \text{partial } \eta^2 = .05$. The main effect for age group was also significant, $F(2,98) = 12.75, p < .001, \text{partial } \eta^2 = .21$. Averaged over jump and anti-jump trials, older children (272 ms) were significantly faster to correct than 8-9 year-olds (298 ms) who, in turn, were faster than 6-7 year-olds (314 ms).

1-way ANOVA on the mean ToC2 showed an overall age effect, $F(2, 113) = 14.33, p < .001, \text{partial } \eta^2 = .20$. Post-hoc tests using Tukey's HSD indicated that older children (506 ms) were significantly faster than mid-aged (571 ms; $p = .005, \eta^2 = .12$) and younger children (618 ms; $p < .001, \eta^2 = .26$); the latter two groups were not shown to differ ($p = .06, \eta^2 = .06$).

Post correction time

A 2-way ANOVA showed no significant interaction between group and jump/anti-jump trials on PCT, Wilks' $\Lambda = 1.00$, $F(2,94) = 0.22$, $p = .80$, partial $\eta^2 = .005$. PCTs were faster on jump trials (431 ms) than anti-jump (509 ms), Wilks' $\Lambda = .60$, $F(1,94) = 62.78$, $p < .001$, partial $\eta^2 = .40$. The main effect for age group was significant, $F(2,94) = 6.73$, $p = .002$, partial $\eta^2 = .13$. Averaged over jump and anti-jump trials, 10-12 year-olds (443 ms) and 8-9 year-olds (475) did not differ significantly, while the former were faster than 6-7 year-olds (509 ms).

Errors

Overall, there was no difference between age groups on the mean number of AEs, $p = .19$: 6-7 year-olds (1.4), 8-9 year-olds (0.9), and 10-12 year-olds (1.2). For TDEs, there was a significant age effect: younger children committed more errors (5.5) than 8-9 year-olds (4.0) and 10-12 year-olds (4.0), $F(2,101) = 4.94$, $p = .009$, partial $\eta^2 = .09$. There was no difference between age groups on the number of CTEs, $p = .25$, partial $\eta^2 = .07$: 6-7 year-olds (1.3), 8-9 year-olds (0.5), and older children (0.6). Finally, a 1-way ANOVA on AJEs revealed no difference between age groups, $p = .45$, partial $\eta^2 = .04$: 6-7 year-olds (1.4), 8-9 year-olds (0.6), and older children (0.8).

Discussion

This study investigated how online control develops across childhood and the extent to which it is constrained by demands on (inhibitory) executive control in three different age-groups: 6-7 year olds (younger), 8-9 year olds (mid-age) and 10- 12 year olds (older). Consistent with our predictions, we found that the pattern of performance on non-jump trials was similar between age groups. However, when a target perturbation was applied at movement onset, children in the younger group showed disproportionately slower movement time compared to both mid-aged and older children, as well as slower reaching trajectory

corrections. Furthermore, when we imposed the inhibitory demand (instructing children to move their arm to the side opposite the target perturbation, i.e., anti-jump trials), we found that younger children continued to show delayed changes in trajectory and slower movement times compared with older children; indeed, the group difference on MT increased from around 150 ms for jump trials to around 250 ms for anti-jump trials. Interestingly, the performance of mid-aged children was compromised relative to the older group on anti-jump trials, but regressed away from older children on anti-jump trials this was evident on both movement time and a delay in the reaching trajectory away from the illuminated target towards the correct target. This pattern is broadly consistent with the hypothesis that the ability to enlist online control is not linear in development, but depends on the nature of the task constraints and associated load on executive control systems. We argue that the ability to utilise predictive control as a means of reducing the latency of online corrections is well developed by 8-9 years of age. However, in cases where rapid online control must be implemented under conditions of real-time inhibitory load (*viz* anti-jump conditions), then the performance of mid-aged children is somewhat constrained. By 10-12 years, children are better able to integrate the demands of both online and executive systems in the service of a goal-directed action. These findings are discussed in further detail below.

Non-jump trials

As predicted, an age-effect on RT was observed. Specifically, older children tended to initiate movement more quickly than mid-age children and younger children. This finding accords with earlier developmental research where performance of typically developing primary-school aged children was compared on the double-step reaching task (Hyde & Wilson, 2013). Since the time taken to initiate reaching towards a prepotent visual target likely reflects information/neural processing efficiency (Wilson & McKenzie, 1998), this pattern of results supports developmental literature suggesting increased processing

efficiency between the ages of 5 and 12 years, linked to white matter maturation among other factors (Barnea-Goraly et al., 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

The mean MT of each group was similar on non-jump. Simple, stimulus-driven movements of this type place minimal demands on online control (and hence predictive modeling). Computationally, since the target remains stationary throughout the movement; discrepancy between the expected (according to the predictive model) and actual consequences of action is minimal, assuming that the initial motor command is accurate (Desmurget & Grafton, 2000). Accordingly, in light of current accounts of motor control (i.e. Shadmehr, Smith, & Krakauer, 2010), our results suggest that the ability to complete rudimentary movements within peri-personal space is well developed by 5 years of age (e.g. Chicoine et al., 1992). Importantly, the similar movement times observed across age-groups here on non-jumps highlights that the developmental differences we observed for jump and anti-jump reaching cannot be explained by general maturation of the motor system but rather by the unfolding of specific control systems (i.e. predictive modeling and executive functioning). This argument is taken up below.

Jump trials

Like earlier studies (e.g. Castiello et al., 1998; Farnè et al., 2003; Hyde & Wilson, 2011a; Paulignan et al., 1991), MT increased from non-jump to jump trials. This is explained by the added processing demands in detecting target perturbation and then implementing a corrective shift in movement trajectory (which itself was longer in distance). The additional time taken to implement the anti-jump movement can be attributed to the demands imposed on inhibitory processing and the associated requirement that children withhold the prepotent response to the cued location and then implement a movement to the opposite side.

Younger children were disadvantaged by target shifts relative to mid-aged and older children, as shown by the significant interaction between age and trial type on MT. Whereas

there was significant difference between groups when the target remained stationary, younger children were slower to adjust on jump trials: *MTdiff* scores were significantly longer for younger children (393 ms) compared with both mid-aged (286 ms) and older children (253 ms). This pattern replicates an earlier study by our group (Hyde & Wilson, 2013). Across both studies, the slower adjustments to target perturbation shown by younger children suggests that the process of motor prediction that supports rapid online control is less efficient in younger children but develops rapidly after the age of 6-7 years. Indeed, the performance of 8-9 year-olds was not significantly different to that of older children on standard jump trials, suggesting a more gradual trend in development from middle childhood. Analysis of kinematic variables further support this view: correction of the reaching trajectory occurred later for younger children (309 ms) compared with both mid-aged (292 ms) and older children (269 ms), with the latter two groups not shown to differ significantly. Importantly, ToC reflects the stage in reaching where *internal* feedback signals are integrated with the motor command to initiate correction away from the initial direction of movement. Higher ToC suggest that this aspect of predictive control is not fully integrated into the motor system of younger children. Taken together, our results for jump performance supports a growing body of evidence suggesting that online control (i.e. predictive modeling) mechanisms undergo rapid developmental change between the ages of 6 and 8 years, with less marked change during the later stages of childhood (Casey et al., 2008; Casey et al., 2005; Johnson, 2005, 2011). Other data suggest that further changes occur after the age of 12 years and into early adulthood, although the exact trajectory is unknown (Hyde & Wilson, 2013).

Anti-jump trials

Crucially, we observed significant group differences between mid-aged and older children on MT when an inhibitory load was imposed on the movement following target

perturbation. This was shown by progressively smaller AMT_{diff} scores with age: the difference in MT between non-jump and anti-jump trials was greater in 6-7 year-olds (750 ms) than 8-9 year olds (610 ms), whose score, in turn, was greater than the older children aged 10-12 years (524 ms). In contrast, no such difference between mid-aged and older children was observed on MT_{diff} scores.

On the kinematic data, there was a tendency for children to perform a two-step correctional process: first an initial correction towards the illuminated target prior to re-directing their reach in a second stage towards the opposite target location. This pattern of performance is a stable characteristic of healthy adults when performing similar tasks (e.g. Cameron et al., 2009) The lack of condition effect when comparing this initial ToC measure on anti-jump trials to ToC values measured during jump trials suggests that the hand's 'automatic pilot' is initially drawn to the illuminated target (Cameron et al., 2009; McIntosh, Mulroue, & Brockmole, 2010; Striemer, Yukovsky, & Goodale, 2010). Importantly, the second corrective movement (i.e. ToC2) indicates conscious and purposive inhibition of the nervous system's tendency to reach toward a prepotent (yet incorrect) target before re-directing the hand to the opposite (correct) target. Our data confirms this pattern and showed that younger and mid-age children not only took longer to make the first automatic correction, but also took significantly longer (618ms and 571ms respectively) to inhibit their response from the cued location than older children (506ms). In contrast on standard jump trials, children were merely required to correct their reaching toward the new stimulus location, the shifting target serving to bias trajectory in, at least, a spatially meaningful way. The pattern of performance for anti-jump trials supports the hypothesis that mid-aged children are less efficient at implementing online control when demands on inhibition are imposed, performing more like younger children than older.

This suggests a crucial transition in both executive control and motor systems during middle childhood, an age where motor control is thought to transition to a well-integrated system of feedback and feedforward mechanisms (Pellizzer & Hauert, 1996). During this same maturational period, frontal executive systems undergo a period of rapid growth and brain connectivity which sees executive systems exert more (top-down) control over behaviour (Durstun et al., 2006). However, some theorists point to a lag period during which the child learns (implicitly) to harness or couple these emerging frontal networks to other systems (Johnson, 2011). In the case of adaptive online control, the child must learn to couple frontal executive systems to the more automatic online control systems of the dorsal stream. As such, we might expect to see a performance decrement in middle childhood when a task places demands on both systems; experience-dependent learning to that point in development is perhaps not sufficient to build an integrated network of top-down modulation.

Taken from the perspective of interactive specialization, maturation of different cortical zones can change how previously acquired cognitive functions are represented in the brain (Johnson, 2011). That is to say that the same behaviour could potentially be supported by different neural substrates at different ages during development. Developmental studies of children reveal that cognitive processes emerge at different points in time, each showing its own maturational trajectory (Anderson, 2002; Garon, Bryson, & Smith, 2008). In general, executive function develops rapidly during the primary school years and then continues at a slower pace during adolescence (Anderson, 2002). During this time, the emergence of complex processes such as set shifting, working memory and inhibition may take some time to be integrated efficiently with existing processes, perceptual-motor and other. The question here is to assess is how inhibitory control becomes integrated into functional systems of motor control.

At a neural level, behavioural improvements in inhibition appear to be paralleled by refinements in the underlying brain activity in the PFC and in networks that include the PFC (Durstun et al., 2006). We know that frontal systems reach a peak in synaptogenesis during early childhood, and that structural MRI shows a progressive increase in myelination along anterior-to-posterior pathways over childhood and adolescence, including reciprocal connections to the PPC (Bunge & Wright, 2007; Durstun et al., 2006). Indeed, diffusion tensor imaging research also suggests that white matter development underlies an important role with mechanisms that shape cognition (Barnea-Goraly et al., 2005), and subcortical structures may play a role in rapid adjustments to target perturbations (Day & Brown, 2001). While these structural changes occur rapidly over early development, the degree of functional coupling that occurs along these networks appears to be more protracted. The online control system that supports (simple) goal-directed reaching is quite functional by early childhood, but undergoes significant change between 5 and 8 years. However, the difficulty that mid-aged children had with online adjustments under an inhibitory load supports the hypothesis that coupling between anterior and posterior systems takes some time to fully emerge. Our data show that the coupling unfolds rapidly between middle and later childhood, while experience-driven learning continues to influence the development of motor and executive systems

In terms of attentional shifts to abrupt-onset cues, the consensus of opinion is that the process of engagement and disengagement is largely a motor preparatory process (Rizzolatti, Riggio, & Sheliga, 1994). More specifically, the putative disengagement process has been conceptualised as an aspect of inhibitory motor control (Mandich, Buckolz, & Polatajko, 2003). As such, it could be argued that the effects we observed for the jump trials could involve aspects of motor inhibition. For anti-jump, the inhibitory demand is such that more controlled, frontal processing is required to counter the compelling effect of the cued target

location on motor planning and, hence, hand trajectory. . Further research is needed to disentangle these components of attention and motor control as a function of task complexity.

Limitations

For repeated movements during which we experience error between the intended action and incoming sensory information (i.e. a target shift), it is possible that a memory representation builds up for the adjusted movements (Shadmehr et al., 2010). In other words, the repeated corrections to limb position could act as a training signal for the brain. This has been observed for actions involving mechanical perturbation of the moving limb: the motor memory associated with the effects of the perturbation may provide advance information for subsequent motor commands. However, when this logic is applied to the paradigm used in our study, it is unlikely that memory effects would accrue over repeated arm movements because there were only a limited number of jump/anti-jump trials within a given block, and those that did were interspersed randomly. Furthermore, we counterbalanced the order of jump and anti-jump conditions to ensure learning effects were minimised. In future, we could vary the probability of jumps and also compare early and late trials on our task to resolve memory-related effects from predictive control per se.

Conclusion

For some time now, the maturational viewpoint has been a widely adopted explanation of motor development in children. Maturational theories seek to interpret emerging sensory, motor and cognitive functions in terms of the development of particular regions of the brain, usually specific areas of cerebral cortex. Alternatively, under the assumption of interactive specialisation, a new cognitive function or skill is acquired through the re-organisation of interactions of different brain structures and regions. Our results are broadly consistent with this view as they show that age-related variation in the ability to implement rapid online is contingent on (frontal) inhibitory constraints. By middle childhood,

online adjustments can be implemented as quickly as those seen in later childhood. However, when demands are imposed on executive systems (as per anti-jump trials) online corrections are slowed in mid-aged children relative to older. Rapid maturation of executive systems during this period may constrain the flexibility with which online control can be implemented. More precisely, the ability to modulate online control via the inhibitory system requires a more protracted period of development over childhood.

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Table 1

Descriptive Statistics of Age Groups in the Double Jump Reaching Task

	Age		Gender		Handedness	
	<i>M</i>	<i>SD</i>	Male	Female	Right	Left
6-7 years (<i>n</i> = 38)	7.1	0.6	14	24	33	5
8-9 years (<i>n</i> = 50)	8.9	0.6	26	24	48	2
10-12 years (<i>n</i> = 41)	10.6	0.5	16	25	38	3

Note. *N* = 129

Table 2

Descriptive Statistics for the Double Jump Reaching Task on Chronometric and Kinematic Variables

Age Group	Trial Type	RT (ms)		MT (ms)		ToC (ms)		ToC 2 (ms)		PCT (ms)		AE		TDE		CTE		AJE	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
6-7 Years	Non-jump	554	75	469	74	–	–	–	–	–	–	2.85	2.07	5.21	3.36	–	–	–	–
	Jump	580	95	837	158	309	46	–	–	468	62	0.81	0.85	6.10	2.74	1.90	2.08	–	–
	Anti-jump	590	114	1236	238	319	39	619	99	549	112	0.54	0.71	5.14	2.96	0.60	1.58	1.36	2.01
8-9 Years	Non-jump	488	71	476	82	–	–	–	–	–	–	2.00	2.14	4.53	2.95	–	–	–	–
	Jump	511	87	727	92	292	45	–	–	433	63	0.44	0.60	3.89	2.53	0.81	1.17	–	–
	Anti-jump	480	85	1080	160	303	41	571	83	516	96	0.38	0.78	3.66	2.25	0.25	1.00	0.63	1.20
10-12 Years	Non-jump	455	60	434	79	–	–	–	–	–	–	2.26	2.36	4.11	2.93	–	–	–	–
	Jump	458	80	681	80	269	26	–	–	408	65	0.57	0.95	4.11	2.47	1.00	1.37	–	–
	Anti-jump	472	70	984	152	273	26	499	82	477	91	0.63	0.94	3.92	2.76	0.18	0.53	0.82	1.38

Note. RT = Reaction Time, MT = Movement Time, ToC = Time of Correction, ToC2 = Second Time of Correction, PCT = Post Correction Time, AE = Anticipatory Error, TDE = Touch Down Error, CTE = Centre Touch Error, AJE = Anti-Jump Error, ms = Milliseconds.

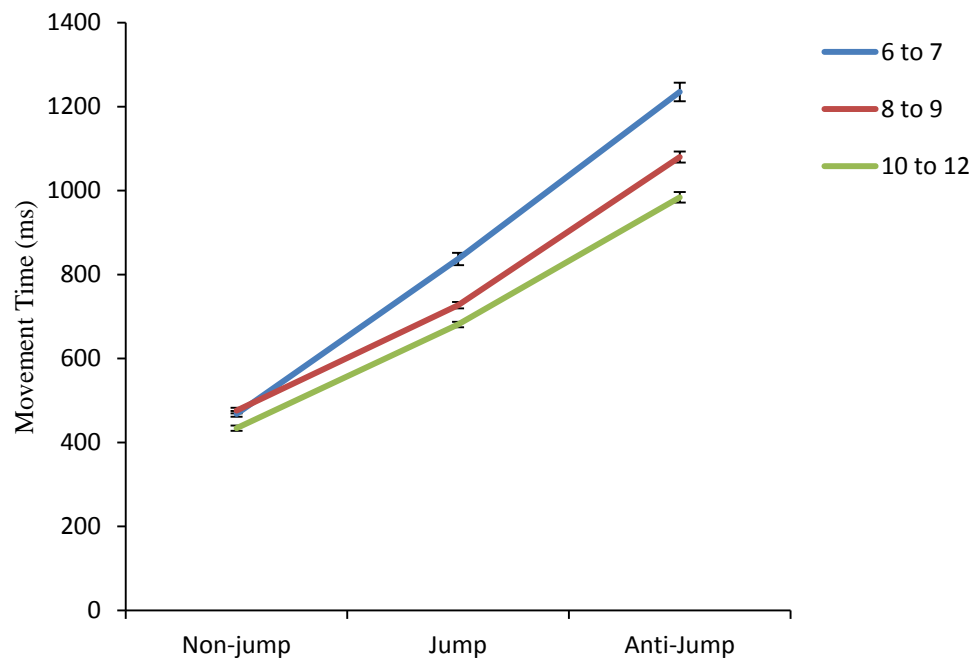


Figure 1. Mean movement time (MT \pm SE) values for age groups on the double-jump reaching task

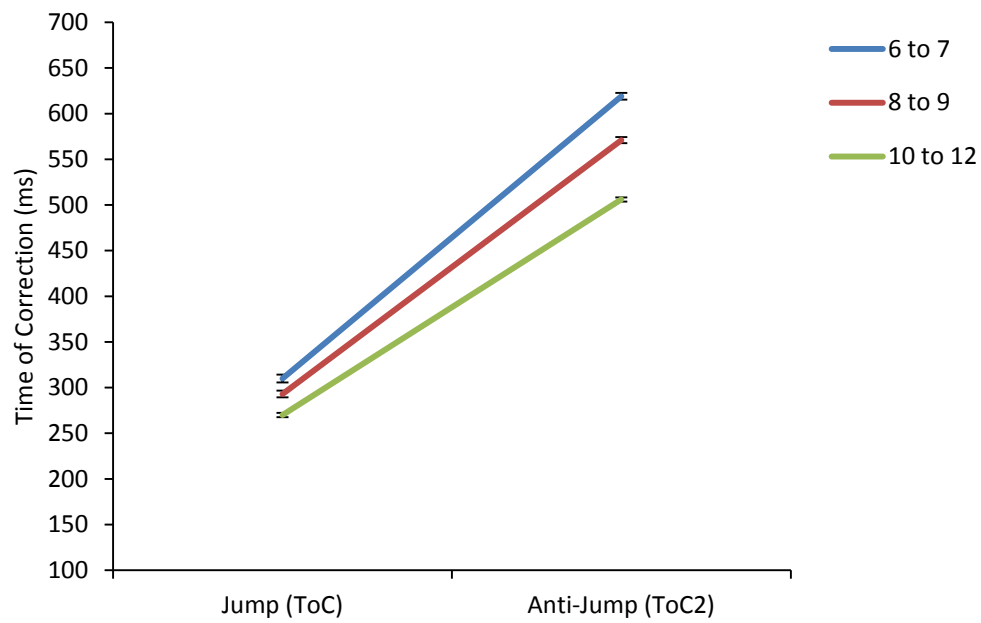
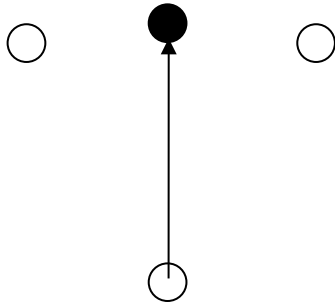
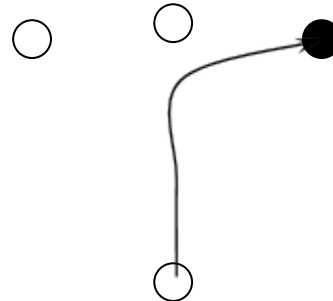


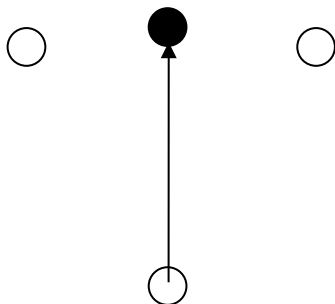
Figure 2. Mean time of correction on jump trial and second time of correction on anti-jump trial (ToC and ToC2 \pm SE) values for age groups on the double-jump reaching task.

Condition A**Non-jump trial**

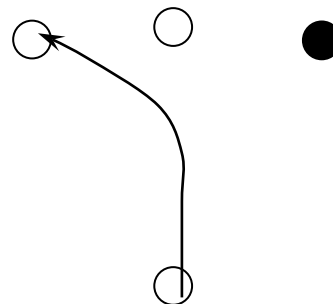
The central target remains lit until touchdown.

Jump trial

The central target displaces to either peripheral location at finger lift off.

Condition B**Non-jump trial**

The central target remains lit until touchdown.

Anti-jump trial

The central target displaces to either peripheral location at finger lift off. Then, the participant reaches to the target on the opposite side.

Figure 3. Experimental set-up of double jump reaching task for non-jump, jump, and anti-jump trials.

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