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RESEARCH ARTICLE

Children's head movements and postural stability as a function of task

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Abstract Manual dexterity and postural control develop throughout childhood, leading to changes in the synergistic relationships between head, hand and posture. But the postural developments that support complex manual task performance (i.e. beyond pointing and grasping) have not been examined in depth. We report two experiments in which we recorded head and posture data whilst participants simultaneously performed a visuomotor task. In Experiment 1, we explored the extent to which postural stability is affected by concurrently performing a visual and manual task whilst standing (a visual vs. manual-tracking task) in four age groups: 5–6 years ($n = 8$), 8–9 years ($n = 10$), 10–11 years ($n = 7$) and 19–21 years ($n = 9$). For visual tracking, the children's but not adult's postural movement increased relative to baseline with a larger effect for faster moving targets. In manual tracking, we found greater postural movement in children compared to adults. These data suggest predictive postural compensation mechanisms develop during childhood to improve stability whilst performing visuomotor tasks. Experiment 2 examined the extent to which posture is influenced by manual activity in three age groups of children [5–6 years ($n = 14$), 7–8 years ($n = 25$), and 9–10 years ($n = 24$)] when they were seated, given that many important tasks (e.g. handwriting) are learned and performed whilst seated. We found that postural stability varied in a principled manner as a function of task demands. Children exhibited increased stability when tracing a complex shape (which required less predictive postural adjustment) and decreased stability in an aiming task (which required movements that were more likely to perturb posture). These experiments shed light on the task-dependant relationships that exist between postural control mechanisms and the development of specific types of manual control.

Keywords Posture development · Motor control · Gaze · Motor development · Manual control · Seated posture

General introduction

Childhood development is associated with the acquisition of an astonishing number of skilled behaviours. One reasonably well-documented example is the ability to accurately direct gaze to stationary and moving targets—a skill that requires the coordinated movements of the head and eyes (von Hofsten and Rosander 1996). Another example is the acquisition of postural control, whereby a crawling infant gradually transforms into an adult who can maintain stable standing posture for prolonged periods of time (Hayes 1982; Hatzitaki et al. 2002). The ability to move the hand skilfully in tasks such as reaching-to-grasp is likewise refined over the developmental trajectory (Schneiberg et al. 2002). Observation over long time periods of any of these behaviours—gaze, posture or hand control—suggests a steady 'linear' progression of the skill across childhood. Nevertheless, inspection of the behaviour over shorter time periods suggests a far more chaotic situation where skills are acquired but can disappear before re-emerging (Kirshenbaum et al. 2001).

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One reason that individual skills often do not follow straightforward developmental trajectories is because they do not develop in isolation but rather rely on the development of other underpinning skills. For example, manual skills require accurate visual information so that execution errors can be detected and corrections implemented. The quality of visual information is directly linked to the steadiness of the head, which is determined by the stability of the postural base. Thus, poor postural stability will affect the precision with which arm movements can be controlled, meaning that the development of manual skills is in part reliant on the current stage of development of postural control. This is evident from infancy where a certain degree of head and trunk stability is necessary before a child can develop reaching and grasping behaviours (Graaf-Peters et al. 2007; Lobo and Galloway 2008). Furthermore, infants who have newly learnt standing show improved postural stability if they are engaged in manual behaviour whilst standing, compared to just standing without purpose (Claxton et al. 2013).

Such patterns of behaviour suggest that the need for better manual skill acts as a driver to the postural system (Haddad et al. 2013), which would explain why posture becomes increasingly stable over childhood, even after the basic level of 'not falling over' has been reached. Indeed, stable adult-like posture only becomes evident around the age of 12 years (Peterson et al. 2006; Ferber-Viart et al. 2007; Mallau et al. 2010), emphasising that learning to stand or walk are only the more obvious milestones within a child's prolonged postural development.

The importance of postural stability within visual-motor skill development can also be illustrated by considering the manner in which one type of movement influences another. For example, fixating between targets or visually tracking a moving target often involves head movements (HMs) but movements of the head have consequence for postural stability (Sugden 1992; Schärli et al. 2013). Likewise, moving the arm when standing causes shifts in the centre of mass (COM)—shifts that require postural compensation if the individual is to (1) remain standing and (2) continue to obtain stable visual information for the purpose of accurately guiding the hand (Berrigan et al. 2006). The ability to make anticipatory postural adjustments (APAs) to cancel out forces generated by hand and/or HMs (Massion 1992) have been shown to develop from infancy onwards to support the development of manual behaviours such as reaching-to-grasp (Van Der Fits et al. 1999; Girolami et al. 2010).

Postural control's development in support of specific visual and manual behaviour has been considered previously. Schärli et al. (2013) examined developmental trends (from 6 years to adulthood) in how visual-tracking behaviour (without concurrent manual behaviour) affects centre of pressure (COP) and head rotation (HR). They found improvement with age in both HR and COP displacement for both a fixed gaze and exploratory gaze condition (where children were shown a brief video clip). HR and COP displacement was greater for exploratory gaze in children, whilst in adults, HR but not COP was greater for exploratory gazes, suggesting that the ability to limit the impact of head rotations on underlying postural stability develops over time.

Posture's role in the execution of basic manual behaviours has also received attention. Sveistrup et al. (2008) examined coordination of trunk and head control in 3- to 11-year-old children and adults whilst making seated reaching movements. In children, 'head-stabilised-in-space' (HSS) strategies for coordinating head and trunk during a reach became more prevalent with age. Meanwhile in adults, postural coordination became further refined as 'head-stabilised-on-trunk' (HST) type control emerged in the roll plane of movement, whilst HSS type control was still seen in both pitch and yaw planes, further increasing stability for vision. Haddad and colleagues conducted two studies looking at posture whilst performing a manual posting task (slotting a block through a hole of varying size whilst standing) in 7- and 10 year olds and adults. In the first study (Haddad et al. 2008), COP became more deterministic with age, indicative of smoother and more predictable trajectories. This was interpreted as indicating an increasing ability with age to make compensatory postural adjustments during precision manual tasks. This interpretation was supported by a second study (Haddad et al. 2012), in which task difficulty was manipulated by varying the aperture size for posting, light level and reach distance to the slot. The results showed that 7 year olds had a relatively low degree of coordination between COP and wrist movements, whilst 10 year olds and adults showed more evidence of compensatory strategies. For 10 year olds, however, this degree of coordination decreased as task demands increased, implying their ability to use postural adjustments was still undergoing development. Taken together, these findings indicate clear developmental trends in postural control. However, whilst postural control appears highly integrated into supra-postural tasks, the nature of this integration also appears to be highly task-dependent (e.g. see Mitra et al. 2013). This issue of task specificity in postural control prompted us to conduct two studies exploring the relationship between the postural and visuomotor control systems across childhood for a range of tasks.

Schärli et al.'s (2013) experiments illustrate task specificity in postural control whilst performing various visual tasks, whilst Haddad et al's (2012) work shows differences dependent on task complexity within a series of visuomanual tasks. To our knowledge, no study has directly examined differences in postural control between visual-only compared to visuomanual behaviours. Thus, in Experiment 1, we chose to explore the extent to which postural stability was affected by the differing task demands of performing a visual-only or manual-tracking task, whilst standing, across the developmental trajectory. This logically extends Haddad et al's (2008, 2012) and Schärli et al.'s (2013) work, moving from considering task-specific posture *within* visual or visuomanual tasks to investigating differences in postural control *between* visual-only and visuomanual tasks.

Given that the rate of development of postural stability is expected to be dependent on the demands of the exact task being performed, Schärli et al. (2013) stressed a need for research to examine how posture develops in support of naturalistic and ecologically relevant behaviours. Thus, in a second experiment, we sought to explore developmental trends in postural control whilst participants performed naturalistic visuomotor behaviours. We took the standing visual-tracking task used in Experiment 1 and adapted it to create a series of tasks that participants performed whilst seated at a table, by holding a stylus and using it to interact with a tablet computer (i.e. the digital equivalent of using a pen with paper). The tasks presented on the tablet involved manual manipulation of a hand-held stylus (e.g. tracking moving targets, making aiming movements and tracing shapes) because learning how to manipulate a stylus is a skill of high ecological relevance, underpinning many important everyday activities such as handwriting, drawing and using cutlery (Feder and Majnemer 2007; Prunty et al. 2013). Given that Haddad et al. (2012) observe that the majority of existing studies only consider seated posture's role in relation to basic reaching-to-grasp or pointing behaviours, Experiment 2 was also of value because it explored seated postural stability in support of a naturalistic visuomotor task (stylus manipulation) which has not been widely examined previously. The combined aim of these experiments was to examine stability during visual and manual tasks that place differing degrees of demand on the postural system and thereby gain a better understanding of how task-specific demands relate to postural development.

Experiment 1

The ability to stabilise the visual system so that it can accurately process information to guide manual control e.g. tracking an object, is an important function of the postural system (Stoffregen et al. 2006, 2007). It is also known that moving fixation between stationary targets (or visually tracking a moving target) often involves HMs and these movements have consequences for postural stability (Sugden 1992; Schärli et al. 2013). In this experiment, we were interested in examining the extent to which visually and manually tracking a target would produce postural changes.

In order to explore the relationship between visual tracking and posture, we developed a simple visual display comprising a target moving around a computer screen. Whilst individuals were able to visually track the target using just their eyes, this type of tracking often also involves HMs (e.g. see Stoffregen et al. 2006). We postulated that the visual-tracking task might affect posture for two reasons. First, it is well established that visual information plays a role in the maintenance of postural stability and this role for vision is greater in younger children (Lee and Aronson 1974; Shumway-Cook and Woollacott 1985; Assaiante 1998; Wann et al. 1998; Hatzitaki et al. 2002; Sparto et al. 2006). Thus, the allocation of visual attention to a local moving target may impact upon the ability of the system to use other visual information for postural maintenance. Second, posture might be affected if participants recruit HMs when tracking the target because of the mechanical changes associated with HMs causing shifts in the body's COM (Schärli et al. 2013). The same logic led us to conclude that tracking the target with the hand has the potential to cause further reductions in postural stability as movements of the arm will alter the body's COM. The extent to which posture is affected by such arm movements would depend on the ability of the system to utilise compensatory mechanisms. It is also possible, of course, that the attention resources required in order to manually track a target could influence posture if demands are also made on the cognitive resources involved in maintaining posture.

To investigate these issues, we examined the amount of HR and COP movement associated with a visual and manual-tracking task in order to explore the extent to which each of these tasks affected posture. We studied the impact of these tasks as a function of age and hypothesised that young children would show less ability than older children and adults to compensate for the COM changes wrought by arm movements.

Methods

Participants

Thirty-four healthy individuals with no previous history of ophthalmological or neurological problems formed an opportunistic sample. The participants were categorised into one of four age groups: 5–6 years ($n = 8$), 8–9 years ($n = 10$), 10–11 years ($n = 7$) and a young adult (19–21 years) group ($n = 9$). The children were recruited from and took part whilst attending a local primary school in Leeds, following permission from the Head of the school and the parents. The school allowed researchers to recruit from 3 years groups (1, 4 and 6), which reflected the full developmental range within the school (i.e. from youngest to oldest students). The adults were undergraduate students who volunteered to participate for no recompense. All participants were right handed, as indexed by the hand they stated that they used to write. All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

Procedure

In all conditions, participants stood on a Nintendo Wii-Fit Balance Board (WBB) with their feet shoulder width apart in front of a tablet PC that was placed 50 cm from the participant on a metal stand, the height of which was adjusted to the elbow height of the participant. In all conditions, participants were closely observed by the researcher to ensure they were compliant with their instructions. In the baseline conditions, participants stood for 30 s with their eyes open and for 30 s with their eyes closed. In the visual-tracking task, the participants fixated a circular target (10 mm diameter) that started in the centre of the tablet PC screen (12.5° vertical, 25° horizontal) and after one second began to move sinusoidally in both the horizontal and vertical directions (creating a ‘figure of eight’ spatial path followed by the target). The sinusoid frequency in the vertical direction was twice that of the horizontal (hence the target following a figure of eight shape). For the visual-tracking task, three separate trials were completed at one of three target speeds (see Table 1) and each trial lasted 30 s. In the manual-tracking task, the participants attempted to keep the tip of a hand-held stylus on the centre of the target where the movement of the target was identical to that described for the visual-tracking conditions. Trial order was pseudo-randomised across speed and trial type.

Measurement system

The system was created using a tablet PC (Toshiba Portégé M750) with integrated Bluetooth connectivity. The tablet was used to present the visual stimuli and capture movements of the hand-held stylus in the manual-tracking task (Culmer et al. 2009; Flatters et al. 2014a). In order to obtain a measure of the degree of postural movement about the COM, the WBB was used to measure the participant’s COP (Flatters et al. 2014b). This device has been demonstrated to be sufficiently accurate to determine between-group differences in postural movement (Clark et al. 2010; Young et al. 2011). The WBB was connected to the host PC via Bluetooth and measured the *X* and *Y* position of the participant’s COP (Fig. 1).

Head rotation was measured using a head mounted orientation tracker. The three degree of freedom (DOF) orientation tracker (MTx, XSens, Netherlands) was mounted to a stiff, lightweight, adjustable brace, strapped to the head of the participant and connected to the tablet via a USB cable. This device recorded static (angular position) and dynamic (rate of turn, angular acceleration) information in three orthogonal axes of rotation.

To ensure optimal bandwidth from all three devices, sample data were individually buffered and recorded to a separate data file for each device, with samples for each device individually time-stamped and synchronised to a common start time. Acquisition frequencies of 100, 100 and 60 Hz were achieved for the tablet screen, XSens and WBB, respectively. All data were smoothed after collection using a 10 Hz zero-phase Butterworth filter (equivalent to a 16 Hz fourth order filter).

Measures

Head rotation was calculated as the summed angular rotation of the head about each of the three Cartesian axes over each target speed period. The summed angular rotation about all three axes measured by the XSens was the output metric for angular motion of the head. Root mean square error (RMSE) provided a measure of the distance the participant was from the centre of the moving target dot in mm and was calculated as the Root Mean Square of the distances between reference and participant input position over all samples in the trial. COP movement was measured as the distance subtended by the COP over each testing period. The COP can be interpreted as the projection of the COM of the participant onto the support surface (in this

Table 1 Detailed description of the stimulus (a green dot, 10 mm diameter) movement for each of the three stimulus speeds in Experiment 1

Trial	Horizontal frequency (Hz)	Vertical frequency (Hz)	Mean resultant velocity (mm/s)	Minimum resultant velocity (mm/s)	Maximum resultant velocity (mm/s)
Slow	0.125	0.0625	41.9	28.6	61.1
Med	0.25	0.125	83.8	57.2	122.2
Fast	0.5	0.25	167.7	114.3	244.3

Resultant velocity is calculated from the combined movement in the *X* (horizontal) and *Y* (vertical) screen axes. The horizontal and vertical stimulus movement amplitudes were 200 and 100 mm, respectively

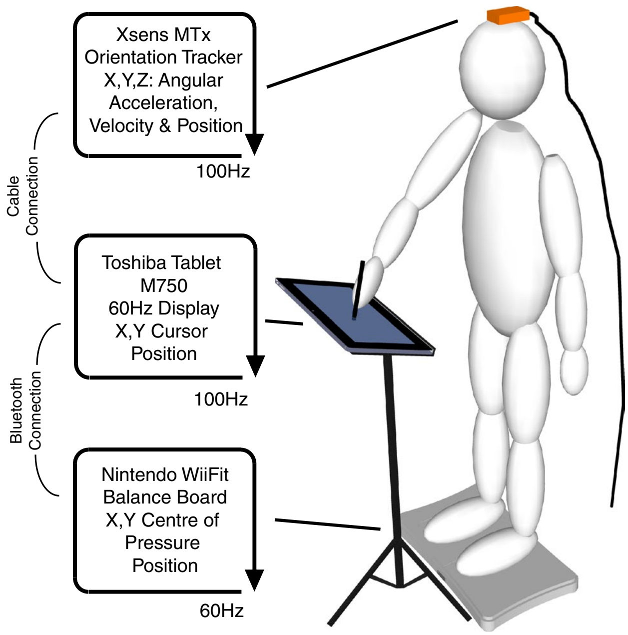

Fig. 1 Schematic of the experimental set-up. Centre of pressure (*COP*) deviation was measured using a Nintendo WiiFit Balance Board with the participants instructed to place their feet shoulder width apart. Visuomotor performance was measured using a tablet PC mounted on a platform adjusted to the elbow height of the participant. Head movement was measured using an Xsens orientation tracker which was mounted to a rigid, adjustable strap on the head of the participant. For the WBB and the tablet screen input, the X and Y axis represents movement (with respect to the participant) in the medial/lateral and anterior/posterior direction, respectively

case the surface of the WBB). The time-course COP movement can therefore be associated with the movement of the COM of the participant.

Results

Statistical analysis

In order to examine the effects of visual tracking on postural stability across the developmental trajectory, we computed a 4 (Within-participant factor; Speed: Baseline vs. Slow vs. Medium vs. Fast) × 4 [Between-participant factor; Age: (children grouped by school year) Year 1 (5–6 years) vs. Year 4 (8–9 years) vs. Year 6 (10–11 years) vs. Adults (19–21 years)] ANOVA for HR and COP data. For the manual-tracking task, using the baseline at fixation would exaggerate effects of Speed and no reasonable measure of manual tracking could be obtained; thus, we computed a 3 (Within-participant factor; Speed: Slow vs. Medium vs. Fast) × 4 (Between-participant factor; Age; Year 1 vs. Year 4 vs. Year 6 vs. Adults) ANOVA for this task. To examine whether differences in posture measures during the visual and manual-tracking tasks could be detected, we took average measures (the arithmetic mean of Slow, Medium and Fast Speeds) separately for HR and COP, and computed a 2 (Task; Visual Tracking vs. Manual tracking) × 4 (Age) ANOVA. Where Mauchly's test indicates a violation of sphericity, p values are adjusted using the Greenhouse-Geisser correction, and uncorrected degrees of freedom are provided. Partial eta-square (η_p^2) values are reported for each ANOVA, and Bonferroni corrections are applied to all pairwise comparisons.

Visual tracking

HR

Faster moving targets increased HR, as evidenced by a significant main effect of Speed [$F(3, 93) = 14.58$, $p < .001$, $\eta_p^2 = .32$]. Post hoc comparisons demonstrated no differences ($p = .155$) between HR at Baseline ($M = 67.92$, SE = 10.52) and the Slow condition ($M = 98.57$, SE = 13.42, $p = .155$). However, all other comparisons reached significance (p's $< .045$), with Medium ($M = 148.51$, SE = 20.57) and Fast ($M = 183.33$, SE = 28.93) speeds resulting in incrementally more HR. There was a significant effect of Age [$F(3, 31) = 8.19$, $p < .001$, $\eta_p^2 = .44$], reflecting the finding that Year 1 had larger HR ($M = 262.04$, SE = 33.07) in comparison with year 4 ($M = 101.76$, SE = 29.58, $p = .006$), Year 6 ($M = 77.76$, SE = 33.07; $p = .003$) and Adults ($M = 56.77$, SE = 31.18). No other comparisons between age groups reached significance (p's = 1.0). Visual inspection of the data (see Fig. 2a) suggested a considerably larger effect of Speed in Year 1, with the magnitude of this effect decreasing with increasing age. Consistent with this, a reliable Speed × Age interaction was also observed [$F(9, 93) = 2.82$, $p = .006$, $\eta_p^2 = .21$]. Decomposing this interaction for Age confirmed these observations, with significant main effects of Speed for Year 1 [$F(3, 21) = 5.01$, $p = .008$, $\eta_p^2 = .42$], Year 4 [$F(3, 27) = 7.87$, $p = .001$, $\eta_p^2 = .47$], and Year 6 [$F(3, 21) = 14.58$, $p = .047$, $\eta_p^2 = .43$], but not for Adults [$F(3, 24) = 1.00$, $p = .362$, $\eta_p^2 = .11$].

COP

We predicted that HMs would be associated with changes in the COP (because of changes caused by or in response to the shifts in the body's COM). Thus, we expected a similar pattern of results when we looked at changes in the COP as a function of fixating the moving target, and this prediction was borne out by the data (Fig. 2b). As with HR, there was a reliable effect of Speed [$F(3, 93) = 7.77$,

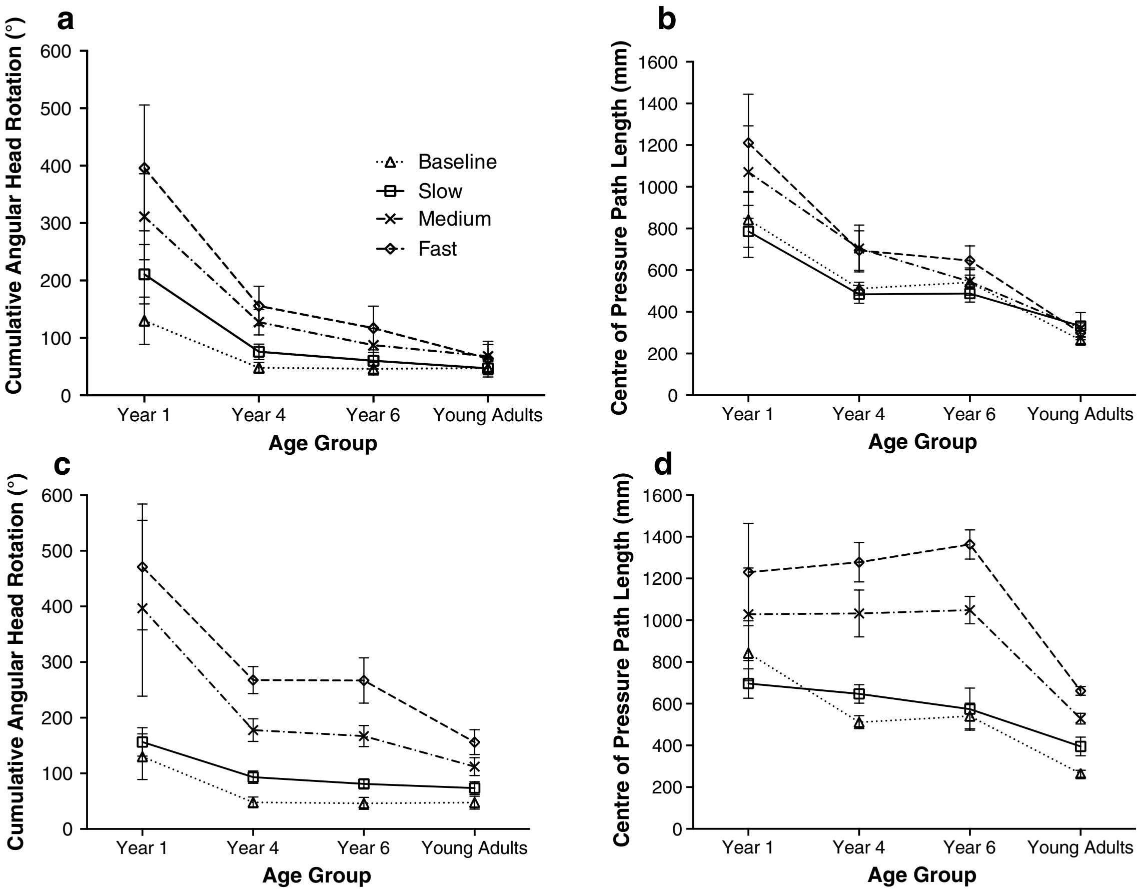

Fig. 2 Head rotation (*HR*) and centre of pressure (*COP*) by age group and speed for both visual and manual target tracking in Experiment 1: **a** HR whilst tracking visually; **b** COP whilst tracking visually; **c** HR whilst tracking manually; **d** COP whilst tracking manually. *Error bars* represent ± SEM

$p < .001$, $\eta_p^2 = .2$]. Post hoc tests revealed the Fast tracking condition ($M = 71.28$, SE $= 6.23$) elicited significantly greater COP displacement in comparison with the Baseline ($M = 53.98$, SE $= 3.46$; $p = .031$) and Slow tracking (52.26, SE $= 3.65$; $p < .001$) conditions. However, Medium speed ($M = 66.04$, SE $= 6.23$; $p = 1.0$) was not significantly different from Fast. Medium was significantly different to Slow ($p = .02$), but no other comparisons reached significance (p's $> .277$). An effect of Age was also apparent in these data [$F(3, 31) = 10.69$, $p = .001$, $\eta_p^2 = .51$], with COP displacement greatest for the youngest group. Pairwise comparisons confirmed this, with Year 1 (97.74, SE $= 8.7$) COP scores significantly larger than Year 4 ($M = 59.87$, SE $= 7.79$; $p = .017$), Year 6 ($M = 55.54$, SE $= 8.7$; $p = .01$) and Adults ($M = 30.40$, SE $= 8.21$; $p < .001$). No other comparisons reached significance (*p's* $> .084$). The Speed × Age interaction showed a similar pattern of results to HR; however, it did not reach significance [$F(9, 93) = 1.78$, $p = .082$, $\eta_p^2 = .15$].

Manual tracking

HR

A reliable effect of Speed [$F(2, 60) = 26.78$, $p < .001$, $\eta_p^2 = .47$] was also observed in the manual-tracking data, with pairwise comparisons showing differences between each tracking condition. The Fast moving targets elicited a larger amount of HR ($M = 294.13$, SE $= 29.73$) in comparison with the Medium ($M = 216.27$, SE $= 38.39$; $p = .005$) and the Slow (101.18, SE $= 7.69$; $p = .003$) conditions, with the Medium speed significantly different to the Slow condition ($p = .003$). A significant effect of Age [$F(3, 30) = 4.1$, $p = .015$, $\eta_p^2 = .29$] reflected the fact that Adults ($M = 114.05$, SE $= 45.93$) showed reduced HMs when compared to Year 1 ($M = 341.46$, SE $= 48.71$; $p = .012$). No other comparisons reached significance (p's $> .115$). There was no reliable Age × Speed interaction (though this approached significance [$F(6, 60) = 2.06$, $p = .071$, $\eta_p^2 = .17$]). See Fig. 2c.

COP

Next, we addressed the question of whether the manual-tracking task affected the COP movement index of postural stability. The pattern was similar to the HR measure (Fig. 2d) with a reliable effect of Speed [$F(2, 60) = 49.16$, $p < .001$, $\eta_p^2 = .62$]. There were significant differences between the Slow ($M = 59.88$ SE $= 2.81$) and Medium ($M = 92.58$, SE $= 6.49$; $p < .001$) condition, between Slow and Fast (115.17, SE $= 8.35$; $p < .001$) and between Medium and Fast ($p < .001$). We also observed a main effect of Age [$F(3, 30) = 5.31$, $p = .005$, $\eta_p^2 = .35$], with same pattern of results as HR; pairwise comparisons demonstrated Adults ($M = 52.69$, SE $= 11.85$) had significantly lower COP displacement compared to Year 6 ($M = 106.89$, SE $= 11.85$; $p = .011$), Year 4 ($M = 98.60$, SE $= 9.91$; $p = .021$) and Year 1 ($M = 98.52$, SE $= 11.08$; $p = .032$). No other comparisons reached significance (p's $= 1$). Again, the Age × Speed interaction approached significance [$F(6, 60) = 1.91$, $p = .094$, $\eta_p^2 = .16$].

Task

HR

A reliable effect of task was found for the HR data [$F(1, 31) = 5.326$, $p < 0.05$, $\eta_p^2 = .15$], with manual tracking leading to larger HR movement ($M = 202.2$, SE $= 23.06$) than visual (143.47, SE $= 20.16$). A significant main effect of Age [$F(3, 31) = 8.37$, $p < .001$, $\eta_p^2 = .45$] reflected the fact that Adults (52.83, SE $= 10.84$) had smaller HR than Year 6 (106.89, SE $= 11.85$; $p = .011$), Year 4 (98.6, SE $= 9.9$; $p = .021$) and Year 1 (98.52, SE $= 11.08$; $p = .032$). No other comparisons reached significance. There was no Task × Age interaction [$F(3, 31) = .15$, $p = .928$, $\eta_p^2 = .02$]. See Fig. 3a.

COP

As with the HR data, a significant main effect of Task [$F(1, 31) = 15.89$, $p < 0.001$, $\eta_p^2 = .34$] was found, indicating greater COP movement during the manual task (88.13, SE $= 5.33$) in comparison with the visual tracking (63.19, SE $= 4.93$). Again, a main effect of Age [$F(3, 31) = 8.85$, $p = .001$, $\eta_p^2 = .46$] was found, with Adults (42.27, SE $= 7.99$) COP scores significantly lower than Year 6 (79.29, SE $= 8.48$; $p = .02$), Year 4 (80.69, SE $= 7.58$; $p = .009$) and Year 1 (100.39, SE $= 8.85$; $p < .001$). No other comparisons reached significance. There was a significant Task × Age interaction [$F(3, 31) = 2.85$, $p = .053$, $\eta_p^2 = .22$], which was driven by the fact that there was no difference in the COP scores between Tasks for Year 1 [$F(1, 7) = .05$, $p = .821$, $\eta_p^2 = .01$], but there was an effect of Task in Year 4 [$F(1, 9) = 8.7$, $p = .016$, $\eta_p^2 = .49$], Year 6 [$F(1, 7) = 10.45$, $p = .014$, $\eta_p^2 = .60$] and Adults [$F(1, 8) = 10.58$, $p = .012$, $\eta_p^2 = .57$]. This result reflects the fact that the manual task elicited large amounts of COP across all the children's groups, but the instability caused by visual tracking reduced with age (see Fig. 3b).

Manual control performance

The manual-tracking task required participants to follow the target with their hand. We explored the effects of speed and age when just considering the manual-tracking accuracy data (Fig. 4). Accuracy decreased as Speed increased [$F(2, 52) = 239.05$, $p < .001$, $\eta_p^2 = .9$]. Pairwise comparisons revealed significant differences across all

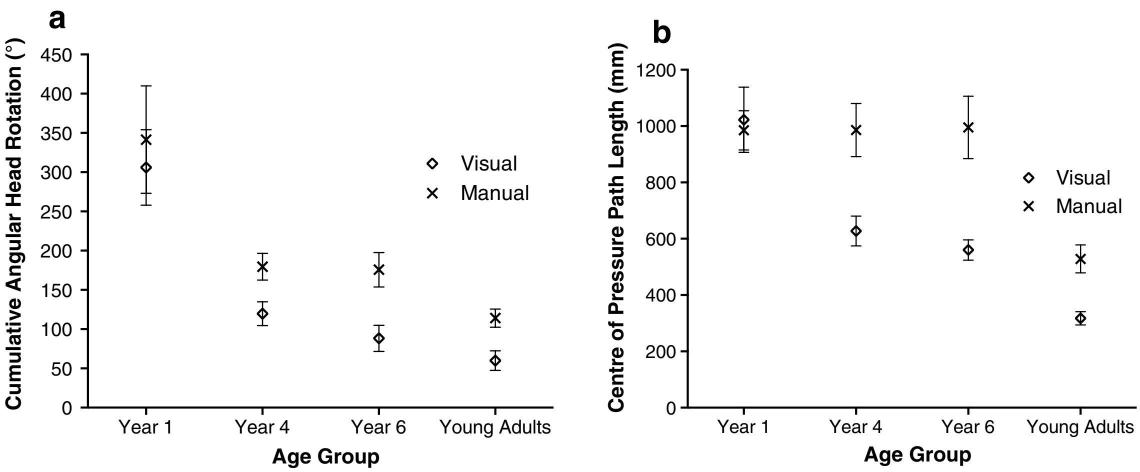

Fig. 3 Head rotation (*HR*) and centre of pressure (*COP*), averaged across target speeds, for age group by task (Visual vs. Manual target tracking) in Experiment 1: **a** head rotation; **b** centre of pressure. *Error bars* represent ±SEM

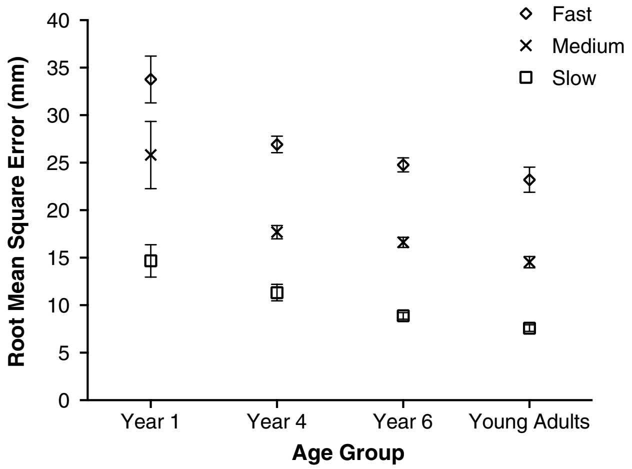

Fig. 4 Accuracy (root mean square error) for manual tracking performance in Experiment 1, by age group and speed of target. *Error bars* represent ±SEM

comparisons (p's < .001), with RMSE scores lowest on the Slow condition ($M = 10.62$, SE $= .48$), increasing for the Medium (18.84, SE $= .98$) and highest for the Fast condition ($M = 27.48$, SE $= .8$). A main effect of Age [$F(3, 26) = 12.42$, $p < .001$, $\eta_p^2 = .59$] was found, reflecting the fact that younger children had the poorest tracking performance, with Year 1 (25.33, SE $= 1.31$) having larger RMSE scores compared to Year 4 (18.82, SE $= 1.23$; $p = .004$), Year 6 (16.64, SE $= 1.42$; $p = .001$) and Adults (15.11, SE $= 1.16$; $p < .001$). No other comparisons reached significance (p's > .222). There was no Speed X Age interaction [$F(6, 52) = 1.54$, $p = .185$, $\eta_p^2 = .15$] for these data.

Experiment 1 discussion

This experiment investigated the development of postural control under varying visual and manual task demands. When comparing between age groups across tasks, the results showed that adults produced less head rotations and COP displacement than children. In addition, the manual tasks resulted in greater HR and COP displacement in all but the youngest age group (i.e. 5–6 years olds), who showed the lowest performance on both the visual and manual tasks. Decomposing these results to look at development within each of the tasks separately (i.e. analysing age effects relative to target speed), there appeared to be a different developmental trajectory for visual and manual postural control. When tracking visually, children but not adults showed sensitivity to the speed of the target, with respect to the amount of HR they produced. Meanwhile, in terms of both HR and COP, the eldest three age groups (8- to 11-year-old children and 19- to 21-year-old adults) performed better than the youngest age group (5- to 6-year-old children) for visual tracking. Meanwhile, when tracking manually, irrespective of age, all participants showed a sensitivity to speed of target, whilst only the Adult group produced significantly less HR and COP displacement compared to any of the child-aged groups. This suggests the ability of the postural system to support manual as opposed to visual tasks may develop at a slower rate.

These results were not surprising and are consistent with emerging evidence regarding the developmental course of the relationship between movements of the head, hand and postural stability. With respect to previous research, Haddad et al. (2012) demonstrated that the rate at which postural stability develops is task-dependent and is moderated by the relative difficulty level of the manual behaviour it is supporting. Research examining vision and posture's integration during childhood also supports this conclusion. Studies in which children were tasked to perform visual tasks of varying difficulty (e.g. saccades versus reading (Legrand et al. 2012) or congruent versus incongruent Stroop tasks (Pia Bucci et al. 2013)), whilst concurrently having their posture monitored, have repeatedly found that increased task demands in the visual domain result in reduced postural stability. Our findings complement this work by demonstrating mature stability developing later for visuomanual, as opposed to purely visual, behaviours that have approximately equivalent aims (i.e. tracking a target). This finding is logical given that manual behaviours are likely to require more attentional resources and integration of a greater number of sensorimotor inputs in order to execute compared to visual-only equivalent behaviours (Pia Bucci et al. 2013). Our results showed that tasks that elicited movements of the head caused displacement of the COP in young children, supporting the hypothesis that HMs affect postural stability (Schärli et al. 2013). In all groups, the manual-tracking task caused greater COP displacement, which provides further support for the hypothesis that movements of the head and hand have consequences for the postural control system. The notable finding was that displacement of the COP decreased as a function of age in tasks that required movements of the arm (i.e. manual tracking) but at a later age than in tasks which only required movement of the eyes (i.e. visual-tracking).

There are two possible mechanisms by which humans might improve their balance abilities over the developmental trajectory. First, the system may become faster in detecting changes in posture (through vision and/or kinaesthesia) and more able to rapidly generate corrective movements in response to these changes. There is no doubt that such refinements occur over childhood and help improve stability in response to unexpected perturbations (Sugden 1992). Improvements in these reactive feedback processes would allow the postural system to maintain greater stability when changes in the centre of gravity (COG) are produced by planned changes in head and arm position. The extent to which movements of the head and arm destabilise an individual would then be proportional to the time taken to respond to the input (i.e. the shift in COG produced by the effector movements). Second, the system may develop predictive control mechanisms where changes in the COG are predicted by internal models and counteracted by postural adjustments that occur synchronously with the head and arm movements. The presence of such anticipatory adjustments would result in minimal displacement of the COP during planned movements of the head and hand. This feed-forward method of postural control requires the system to learn the relationship between movements of the head and hand the resultant changes in the COG.

Inspection of our data provides evidence in support of the notion that predictive mechanisms develop over childhood. The tasks that required participants to move their head and hands had a much smaller impact on the COP displacement in adults than in children. If improved stability is a result of better reactive mechanisms in adults, then one would not expect the COP measure to decrease (as the initial displacement would still be present even if it was corrected in a shorter period of time). Thus, the reduced displacement of the COP with increased age suggests that humans develop the ability to generate stabilising forces that counteract the COG changes associated with given head and arm movements. These results are consistent with a large body of literature that suggests humans have sophisticated internal models (Wing et al. 1997) and that these models develop over childhood (Shadmehr and Mussa-Ivaldi 1994). For example, human adults alter their fingertip forces in a manner that anticipates changes in the inertia of a hand-held object when they move the object from side to side or up and down (Flanagan et al. 1993).

The visual-tracking task that we employed did not necessitate the use of HMs—it was possible for the participants to track the targets using their eyes. The results indicate that this was the strategy adopted by the adults as head displacement did not increase from baseline values in the visual-tracking task for this group. The fact that we did not measure eye movements means there is the possibility that the older participants did not follow our instructions and failed to maintain fixation on the target (i.e. their lack of HM indicates non-compliance with the task). However, we feel that it is unlikely because it suggests that the groups got worse at following our instructions as they got older (if anything the opposite would be expected). Equally, there are principled changes in children's degree HR in response to the speed of the target, which again we would not expect to see if children were non-compliant. It therefore appears that children have less ability to decouple eye and HMs when pursuing a target—the head has a greater role in adults when gaze is shifted to maintain foveation of a moving target.

The fact that children are less able to compensate for these HMs means that visually tracking a moving target creates postural demands for children. It is possible that the less stable posture created by movement of the head is one of the drivers that results in adults being more likely to track the target with their eyes in a task of the type we used. In other words, it is tentatively suggested that the distinctions observed in postural control are due to the differences in the development of the nervous system in being able to manage the demands placed upon it by a task. In order to test this assumption, further investigations are required. Specifically, it is unclear how the relationship between task demands and postural stability across the developmental trajectory might be modulated by the addition of postural support e.g. through seating. Indeed, fundamental manual control skills, such as handwriting, are learnt whilst a child is sat down. Secondly, different tasks place differing degrees of demands on the postural system. For example, aiming tasks are more likely to destabilise the COG and perturb postural control (Shadmehr and Mussa-Ivaldi 1994; Pozzo et al. 2001; Patla et al. 2002; Harbourne et al. 2013) than the tracking task employed here. Thus, clarifying how postural control might vary as a function of task demands is an important step in understanding the relationship between the development of postural and visuomotor control across childhood. We turn to this issue next.

Experiment 2 introduction

The human nervous system requires a stable base in order to foster the development of accuracy and precision in manual control tasks (Colangelo 1993; Bertenthal and von Hofsten 1998). Instability in posture has consequences for manual control (e.g. unpredictable, irreproducible and inconsistent movements). In contrast, a stable postural base allows for the accurate execution of planned movements which results in more predictable outcomes and thus allows the acquisition of a motor command repertoire that can be used for skilful interactions with the environment (Burdet et al. 2006). The difficulty for the developing system is that arm movements disrupt stable posture. This is because the inertial forces elicited by arm acceleration result in the destabilisation of the COG and this perturbs postural control (Shadmehr and Mussa-Ivaldi 1994; Pozzo et al. 2001; Patla et al. 2002; Harbourne et al. 2013). In Experiment 1, the reduced displacement of the COP with increased age suggested that humans develop the ability to generate stabilising forces that counteract the COG changes associated with given head and arm movements over time. In the following experiment, we examine how differing manual tasks, which result in qualitatively different arm movements, might affect postural stability, when we provide additional postural support.

Maintenance of postural stability when engaged in a task requiring manual dexterity is often conceptualised as a 'dual-task' issue (Huang and Mercer 2001; Remaud et al. 2012; Van Impe et al. 2012). It is consistently found that posture is less stable when a concurrent manual control task is undertaken, implying that the nervous system has limited resources at its disposal which must be distributed appropriately between competing task demands (i.e. maintaining balance and performing the manual task). The capacity-limited resources are most stretched when a manual task requires high levels of accuracy and precision. Nevertheless, Haddad et al. (2010) found that young adults were able to increase their postural stability appropriately as the demands of a manual task increased (posting an object through an aperture of decreasing size). In contrast to young adults, children and older adults are less able to cope with 'dual-task' demands as postural control is more effortful and less automated in these age groups (Haddad et al. 2013; Yogev-Seligmann et al. 2008). The progressive refinement of postural control is well documented across the developmental trajectory—from the frequently falling infant to the stable adult (Hayes 1982; Hatzitaki et al. 2002). Notably, it is consistently reported that there are large differences in postural control between younger and older groups of primary school children (Shumway-Cook and Woollacott 1985; Kirshenbaum et al. 2001; Schmid et al. 2005). We partially replicated this effect in Experiment 1, finding significant differences between child-age groups for visual but not manual target tracking. The lack of postural development during manual tasks in this age group perhaps implies that the greater complexities inherent in maintaining posture whilst performing a supra-postural manual task take longer to mature (e.g. have to master integrating a greater range of sensorimotor inputs than during a vision-only task (Pia Bucci et al. 2013)).

It is probable that poor postural control in younger children will directly impact on their ability to execute a manual control task (Smith-Zuzovsky and Exner 2004). Moreover, the perturbations caused by arm movements lead to a conundrum for the maturing nervous system as a stable base is required when developing manual proficiency (Stapley et al. 1999). One simple solution to this conundrum is to sit down. A chair provides postural support and thereby reduces the control demands placed on the nervous system. This is evident in studies that show that the addition of postural support increases movement efficiency, with this effect most pronounced in younger children (Smith-Zuzovsky and Exner 2004; Saavedra et al. 2007). For example, reach-to-grasp movements show adult-like levels of proficiency in 8- to 10-year-old children when they are seated (Schneiberg et al. 2002). Also, the catching performance of children graded as having poor to average performance increases when seated, whilst those graded as expert did not (Angelakopoulos et al. 2005). This previous research suggests that the normal disparities in postural stability across age groups may be attenuated when children are seated. This raises the empirical question of whether a standard school chair provides sufficient support to remove the normal differences in stability observed across primary school children (e.g. when standing). This is an important issue as the majority of fundamental educational skills (e.g. handwriting) are acquired whilst seated at a desk on a standard school chair. This experiment explored whether sitting children on a standard school chair is sufficient to ameliorate the age differences in postural control ability commonly reported when children perform supra-postural manual tasks whilst standing (Haddad et al. 2008, 2012). We were also interested in exploring the extent to which different tasks impact on seated postural stability.

The success of the postural system can be measured by the degree to which it allows the successful execution of goal-directed actions (Riley et al. 1999; Balasubramaniam et al. 2000; Stoffregen et al. 2007). It follows that the postural control demands are a function of the stability required for the successful execution of a particular task (Aruin and Latash 1996; McNevin and Wulf 2002; Stoffregen et al. 2006, Stoffregen et al. 2007). As we observed in Experiment 1, different tasks place differing degrees of demands on the postural system. Here, we build on this work by examining a range of tasks involving manipulation of a hand-held stylus (i.e. tracking moving targets, making aiming movements and tracing shapes). In doing so, we address a recognised need for more research which examines the development of postural stability in combination with *naturalistic* supra-postural tasks (Schärli et al. 2013). Until now, the majority of previous research into seated posture has been limited to examining how seated posture develops to support simple reaching-to-grasp and pointing behaviours (see Haddad et al. 2013). Learning how to skilfully manipulate a stylus is a manual skill of high ecological relevance, underpinning many important everyday activities such as handwriting, drawing and using cutlery (Feder and Majnemer 2007; Prunty et al. 2013). We therefore investigated postural stability and HMs whilst participants performed a battery of tasks that all required manipulation of a stylus. These tasks, whilst being novel and therefore as free as possible from cultural bias, encompassed many of the functional challenges present in everyday tasks requiring stylus use, namely tracking moving targets, tracing shapes and making aiming movements. These tasks tap into specific control mechanisms (tracking relies on the ability to predict target movement, tracing shapes requires precise force control whilst aiming movements rely on accurate, ballistic, feed-forward mechanisms and fast implementation of online corrections). We hypothesised that the tracing task would require (and allow) minimal postural movement. In contrast, we expected that the aiming task would perturb posture as it requires rapid accelerations and decelerations of the arm. The effect of the tracking task was not predictable a priori as the postural adjustments will depend on the ability of the children to predict the movement of the target, although an underlying anticipatory ability required for skilful manual tracking has been shown to increase with age (Van Roon et al. 2008). In standing posture, there is a tightly coupled relationship between HM and centre of pressure displacement so that tasks that require HMs have a destabilising effect on posture. We hypothesised that this relationship would be much reduced in the children when seated.

Methods

Participants

An opportunity sample comprising of three age groups of children, with no history of ophthalmological or neurological deficits, were recruited from a primary school in the north of England (30 male, 31 female). The school permitted recruitment from 3-year groups of children including the youngest to the second oldest year group in the school and with a gap of approximately 12 months between each year group's age range. Year groups were: Year 1 ($N = 14$; 5–6 years), Year 3 ($N = 25$; 7–8 years) and Year 5 ($N = 24$; 9–10 years).

Procedure

Four test stations were set-up in a dedicated room provided by the school. Each station was placed in a corner of the room minimising distractions when concurrently testing multiple participants. The room was artificially lit, with all sources of natural light removed (in order to standardise conditions between children tested at different times of the day). A plywood board (16 mm thick, 1 m^2) was placed on top of a WBB to provide a platform for a school chair and table. Spacers were placed under the table's legs to standardise the height of the chair with respect to the table. The surface of the platform was covered with non-slip floor covering and had a wooden strip added to prevent the chair falling off the platform. Participants were seated at the table with their feet on the plywood board and the facing edge of the table in line with the front edge of the seat. In order to capture the rotation and translation of the head, the participants wore spectacles with the lenses removed. The spectacles had three IR diodes forming two orthogonal axes (both origins at the right-hand hinge) extending in the medial–lateral and anterior–posterior direction. Two IR cameras (Nintendo WiiMote) were used to track HMs. The cameras were calibrated by capturing 300 images of a board comprising four diodes, equally spaced in a 150 mm^2 configuration. The calibration procedure was repeated three times for each station (to ensure that sufficient data were captured to allow for algorithm convergence) and each station was calibrated prior to the morning and the afternoon testing sessions. The total distance subtended by all three diodes during each subtest was used as the absolute measure of HM in mm.

In two baseline subtests, participants were asked to sit: (1) with their eyes closed for 30 s; (2) fixate on a cross drawn on white card and mounted on the tripod immediately in front of them for 30 s. Participants subsequently completed a battery of motor tasks (see Fig. 5), which included tracking, aiming and tracing subtests. For each test, the tablet's screen was provided on a horizontal surface (in landscape orientation), which mimics writing with a pen and paper using a pen-like stylus as an input device. The laptop was placed on the table 10 cm from the participant. An on-screen instruction was displayed immediately prior to the start of each subtest. Acquisition frequencies of 100, 60 and 60 Hz were achieved for the tablet screen, WBB and Ninentdo WiiMotes, respectively. All data were smoothed after collection using a 10 Hz zero-phase Butterworth filter (equivalent to a 16 Hz fourth order filter).

Tracking

In this subtest, participants were asked to use the stylus to keep the tip of the stylus on a green dot as closely as possible as it moved around the screen in a horizontal figure of 8 (the path is defined as a function of a sine wave in the X and Y axes; see Fig. 5a). The trial began when the participant placed the stylus on the target dot in the centre of the screen for 2 s. This was first done with no guide followed by the same subtest but with a background guide to provide information on the spatial path followed by the dot. In each trial, the target dot's speed immediately increased after three paths were completed until nine complete paths of the figure of eight shape were completed (slow, medium and fast). To capture the spatio-temporal accuracy of the participant during the tracking task, the two-dimensional distance from the stylus to the dot centre was calculated across all data points, and a total of six error signals were generated (three speeds and two background conditions). For each of the six error signals, the overall metric of performance was calculated as the RMSE of the signal. To capture the spatial accuracy of the shape subtended during pursuit, a second metric was calculated as the mean of the minimum distances from input to the ideal path across all

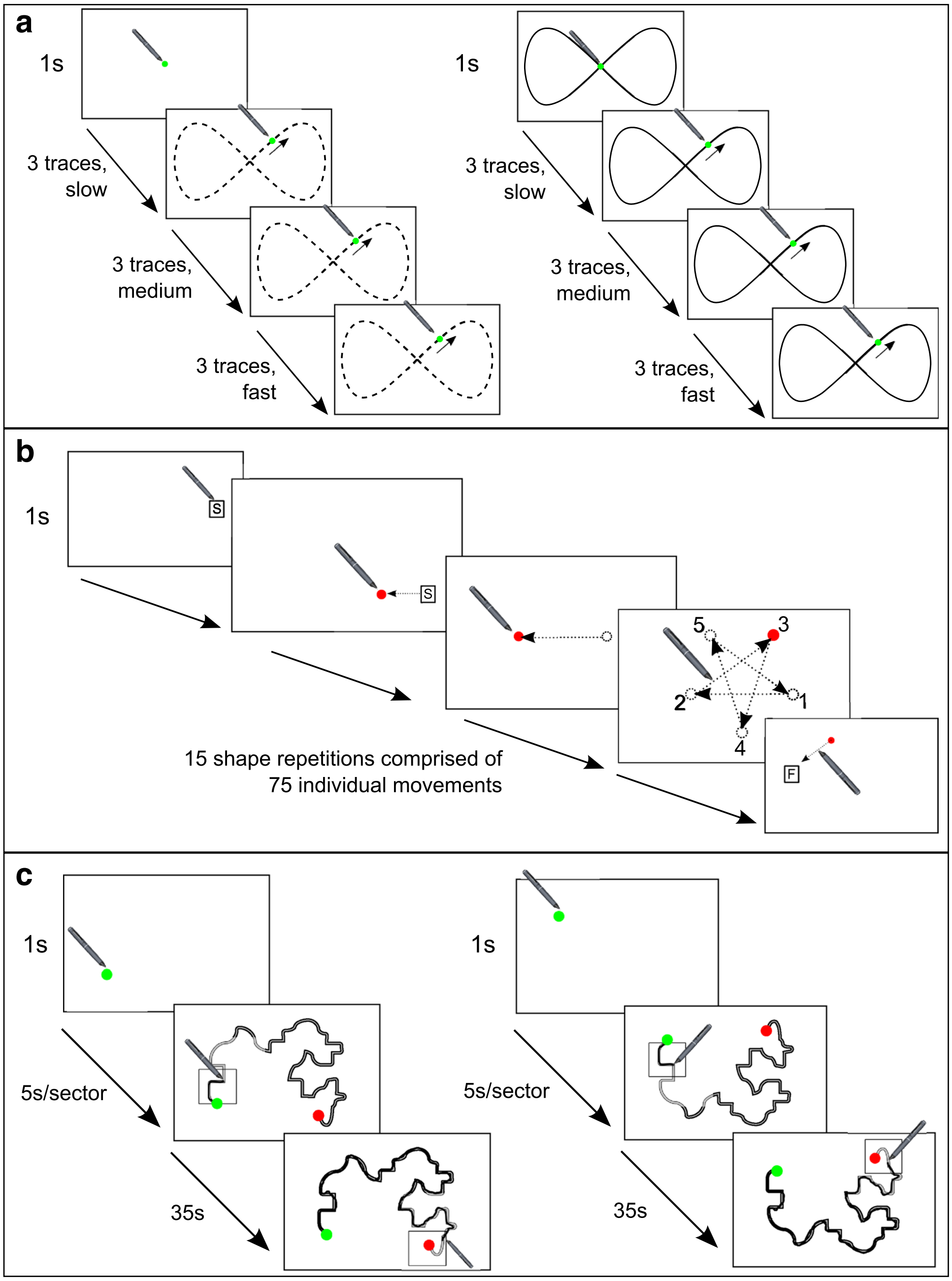

Fig. 5 Illustrations of the three manual control battery tasks: **a** tracking, **b** aiming and **c** tracing. **a** *Left* is a schematic of first Tracking trial (i.e. without 'Guideline'), annotated with a *dotted line* to indicate the trajectory of the moving dot. *Right* is a schematic of the second Tracking trial, which included the additional Guideline. **b** Schematic of the Aiming subtest, annotated with *dotted arrows* implying the movements participants would make with their stylus to move off the start position, between target locations and to reach the finish position. On the *4th panel,* further annotations indicate the locations in which targets sequentially appeared, with *numbers* indicating the sequence in which they were cued. **c** *Left* is a schematic depicting tracing *path A* and *right* is a schematic depicting tracing *path B*. The *black shaky lines* are an example of the 'ink trails' a participant would produce with their stylus in the course of tracing

data points (within each variant). Standard scores were calculated for the spatio-temporal and spatial metrics within age group for twelve measures (two metrics, three speeds and two background conditions), and a composite score for tracking was calculated as the arithmetic average of these twelve values.

Aiming

In this subtest, participants were required to move from one target dot to another without lifting the stylus from the screen (Fig. 5b). The trial began when participants placed the stylus on the 'start' button for 2 s; this prompted the first target dot to appear. When this first target dot was reached, it disappeared and another appeared in a different location on the screen. The subtest was 75 movements long, after which a 'finish' block appeared and terminated the trial once the stylus reached it. Within the final 25 movements, and randomly distributed throughout them, six of the trials would appear to 'jump' to the next target position before the participant had reached it. 'Baseline' trials were denoted as the first 50 trials where no jump events had occurred. 'Embedded' trials were the normal trials in the last 25 movements with 'jump' trials being the targets that changed location mid-movement. The median values of movement time and median Log of the Normalised Jerk (NJ) were calculated separately for movements in the baseline, embedded and jump conditions. These six values were standardised within age groups. A composite score for the aiming task was calculated by averaging the six standard scores.

Tracing

The final subtest required participants to trace a static maze shape as accurately as possible with the stylus (Fig. 5c). The trial was initiated and the maze appeared when the stylus was placed on the 'start' block for 1 s. A hollow box moved along the pattern every 5 s, and the participants were instructed to remain within the box for the duration of the trial (35 s). The trial was finished when the 'finish' block was reached. Participants completed three repetitions of two shapes totalling six tracing subtests. For each of the measured pen screen positions, the minimum 2D distance to the idealised reference path was calculated. The arithmetic mean of these values was taken as a measure of shape reproduction accuracy. Despite continuous monitoring of the participant by the experimenter, a number of participants did not adhere to the instruction to stay within the moving box whilst tracing the shape. In order to control for this effect, we calculated 'penalised path accuracy' (PPA). The ideal trial time, including the 1 s delay at the onset of was 36 s. Any deviation from this time was taken as an indicator of task non-compliance subtest. To normalise path accuracy in the context of task time, path accuracy was negatively scaled with subtest time against the ideal 36 s value. Standard scores were calculated for PPA within age group for each shape. A composite performance score was calculated as the mean of the standard scores for each shape.

Overall battery score

The overall performance composite score was calculated as the arithmetic mean of the tracking, aiming and tracing standardised scores.

Results

Postural stability outcomes (HM and COP) at baseline were calculated as scores obtained when seated with eyes fixed on a stimulus. HM and COP were analysed separately as dependent variables using full factorial mixed ANOVAs that specified Age as a 3-level between-subject independent factor (4–5, 6–7 and 8–9 years) and Task as a 4-level within-subject factor (Baseline, Tracking, Aiming, Tracing). In order to examine whether age effects were present in the manual control component of this study, one-way ANOVAs that used Age as a 3-level between-subjects factor (4–5, 6–7 and 8–9 years) were computed for outcome score on the CKAT battery and on each subtest.

Head movement

The main effect of Age on HM [$F(2, 35) = .88$, $p = .42$, $\eta_p^2 = .05$] and the Age by task interaction term [$F(6, 105) = .66$, $p = .69$, $\eta_p^2 = .04$] were non-significant. However, there was a significant main effect of Task [$F(3, 105) = 15.75$, $p < .001$, $\eta_p^2 = .31$]. Post hoc comparisons revealed Tracing HMs ($M = -0.369$, SE = .076) were significantly lower ($p = .003$) than Aiming ($M = .189$, SE = .167) and Tracking HM ($M = .266$, SE = .244, $p < .001$), but not Baseline (−.41, SE = .07; $p = 1$). Baseline HMs were also significantly lower than Aiming ($p = .005$) and Tracking ($p < .001$) (see Fig. 6).

Centre of pressure

Consistent with HM data, we found no significant main effect of Age on COP [$F(2, 55) = .12$, $p = .89$, $\eta_p^2 < .01$] and no Age × Task interaction [$F(6, 165) = 1.39$, $p = .22$, $\eta_p^2 = .05$] and a significant main effect of Task [$F(3, 165) = 17.86$, $p < .001$, $\eta_p^2 = .25$]. Post hoc pairwise comparisons revealed significantly lower COP displacement for the Tracing task ($M = -.48$, SE = .073) relative to all other comparisons (p's < .01). In contrast, Aiming COP displacement ($M = .5$, SE = .112) was significantly higher relative to Tracking (.024, SE = .09) and Tracing (p's < .001) and marginally higher ($p = .064$) than baseline (.065, SE = .18). No other comparisons reached significance ($p > .05$).

Manual performance

We found significant effects of Age in each of the manual-tracking tasks (see Fig. 7). In Tracking [$F(2, 62) = 22.78$, $p < .001$, $\eta_p^2 = .43$], pairwise comparisons revealed differences between year 1 ($M = -.72$, SE = .13) and 3 ($M = .08$, SE = .1; $p < .001$) but not 3 and 5 ($M = .34$, SE = .10; $p = .175$). Similarly, for Aiming [$F(2, 59) = 14.36$, $p < .001$, $\eta_p^2 = .33$] there were differences between Year 1 ($M = -1.0$, SE = .22) and 3 ($M = .13$, SE = .16; $p < .001$) but not 3 and 5 ($M = .42$, SE = .16; $p = .647$). In the Tracing task [$F(2, 60) = 40.23$, $p < .001$, $\eta_p^2 = .57$], there were significant differences across all age comparisons (p's < .001; Year 1, $M = -1.29$, SE = .18; Year 3, $M = .04$, SE = .13; Year 5, $M = .71$, SE = .14). Finally, a statistically robust main effect of Age was found for the overall CKAT battery too [$F(2, 60) = 37.85$,

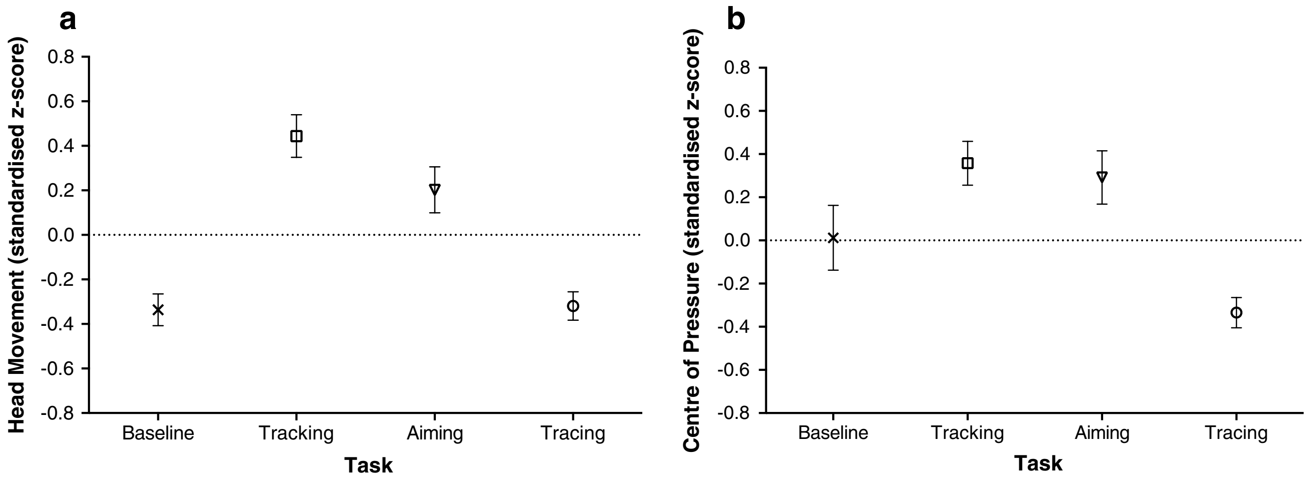

Fig. 6 Standardised scores for head movement (*HM*) and centre of pressure (*COP*) scores whilst performing (*Baseline*) quiet standing versus each of three manual control task battery subtests (Tracking, Aiming and Tracing) in Experiment 2. **a** Head movement; **b** centre of pressure. *Error bars* represent ±SEM

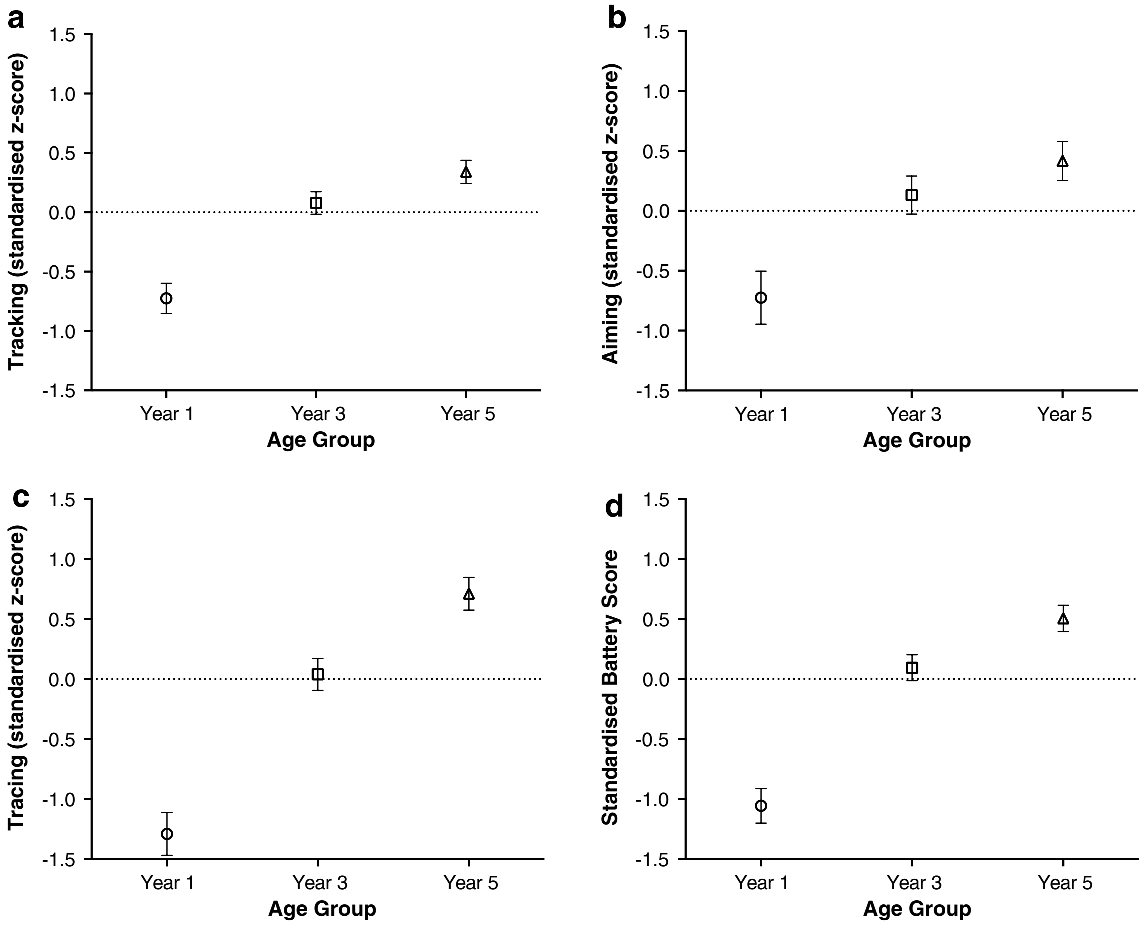

Fig. 7 Standardised *z*-scores for performance on the manual control task battery (and its subtests) by age group in Experiment 2: **a** tracking subtest; **b** aiming subtest; **c** tracing subtest; **d** overall battery score. *Error bars* represent ±SEM

$p < .001$, $\eta_p^2 = .56$], with post hoc tests revealing participants performance increased with age, as evidence by significant differences in comparisons between each successive age group, with Year 1 ($M = -1.06$, SE = .14) scoring significant lower than Years 3 ($M = .09$, SE = .11; $p < .001$) and Year 5 ($M = .51$, SE = .11; $p < .001$) and Year 5 scoring higher than Year 3 ($p = .029$).

Experiment 2 discussion

Experiment 2 investigated the role of seating on postural stability with different manual tasks across three age groups of primary school children. We found that (a) when seated, age-related differences in postural control were not observable, and (b) postural control in seated children was modulated in a principled manner by task demands; so stability is increased when tracing, decreased when generating aiming movements and minimally disrupted when a predictably moving target is manually tracked.

Postural stabilisation is necessary to counteract the consequences of arm movements on the COG (Bernstein 1967; Von Hofsten 1993; Stoffregen et al. 2007). Clear improvements in postural control as a function of age have been demonstrated in a number of studies (Schneiberg et al. 2002; Schmid et al. 2005; Haddad et al. 2012; Harbourne et al. 2013), and a child's ability to make postural adjustments in anticipation of forthcoming perturbations increases with age (Inglin and Woollacott 1988; Schmitz et al. 2002; Girolami et al. 2010). In line with this, the results in Experiment 1 indicate that predictive postural compensation mechanisms for arm movements develop during childhood into adulthood. However, the results from Experiment 2 suggest that whilst seated in a standard school seat this provides enough postural support to attenuate well-established maturational differences observed for postural control during standing supra-postural manual tasks (see Haddad et al. 2008, 2012). It is always difficult to interpret a finding of no significant difference, and it is entirely possible that subtle postural differences existed between the age groups (but we lacked sufficient power to detect) or that maturation of posture to an adult-level of proficiency whilst seated occurs out with the age range (5–10) we studied. Nevertheless, this result is consistent with previous studies that have shown that adopting a seated posture typically attenuates differences due to age and skill in performing reach-to-grasp (Schneiberg et al. 2002) and catching performance (Angelakopoulos et al. 2005). Therefore, it would seem reasonable to conclude that the provision of a seat has a profound effect on the size of the postural differences, even if it does not remove them completely, and that this is the primary explanation for why no age differences were observed in Experiment 2.

To entirely resolve this issue though further research is required. Specifically, research which combines the thematically similar (but not directly equivalent) experiments presented in this paper into one systematic study of postural stabilities' development, in support of manual control, over a consistent age range (up to full adulthood), in both standing and seated scenarios would be useful. Indeed, direct comparison between the two experiments presented in this paper is inadvisable, given the variability in age groupings between the two samples and the lack of direct equivalence between the seated and standing manual tasks. For example, the different dynamics of manipulating a stylus (1) at arm's length whilst standing and (2) with one's arm bent whilst seated at a desk represent a confounding factor that future experiments would need to control for if a direct comparison between the two tasks is to be validly made.

Setting aside empirical comparison based on our results, logic suggests that seating provides a more biomechanically stable base than a standing bipedal one. The additional postural support provided by a seat reduces the demands placed on the nervous system as the disruption to postural stability from arm movements is minimised. It has been shown previously that the increased postural support afforded by sitting results in a reduction in the magnitude of the usually observed APAs made in anticipation of forthcoming COG displacement (van der Heide et al. 2003). A 9-year-old child has a more developed postural system relative to a 5-year-old, which results in superior performance whilst standing. In this context, proficiency in skilled manual control whilst seated is much less dependent upon the ability to stabilise the COG in response to perturbations caused by arm movements.

We examined seated postural control across different manual control tasks and hypothesised that different tasks should differentially impact posture. Consistent with a large body of research, we found that manual tasks modulated postural stability (Aruin and Latash 1996; Bardy et al. 1999; McNevin and Wulf 2002; Stoffregen et al. 2006, 2007). In the tracing task, which required the largest degree of precision, postural COP displacement and HM were minimised. This is consistent with research demonstrating the 'freezing' of degrees of freedom in the body to maintain stability in tasks that have high accuracy demands (Stoffregen et al. 2000; Haddad et al. 2012). In the aiming task, we found the greatest amount of COP displacement with reasonable amounts of HM. This was expected as the dynamic forces generated by the limb during the accelerations and decelerations that occur throughout the task result in a relatively large degree of postural disturbance. This disturbance occurred across all age groups, and it indicates that the children did not completely compensate for the displacement of mass caused by the ballistic nature of the arm movement. In the tracking tasks, the target movements were predictable. As such, the tracking task more readily allowed for the planning of postural adjustments (Burdet et al. 2006), and we found no differences in COP displacement relative to baseline. Previous studies have shown that the speed of the arm movement and the predictability of the task dictate the magnitude of postural adjustments (Cordo and Nashner 1982; Horak et al. 1984; Crenna et al. 1987). In Experiment 1, it was found that the tracking task had a destabilising effect on posture which increased for all ages with increasing speed of the target (possibly mediated by the HMs generated in response to the task demands). Meanwhile, manual ability to track the target improved with age in both Experiments 1 and 2, both times the youngest age group was significantly poorer performers than all others. This result concurs with previous research showing that skilled manual tracking performance is reliant the ability to anticipate and predict movement of the target, an ability that improves with age (Van Roon et al. 2008). Nevertheless, regardless of age-related differences in manual task performance, the provision of a seat appears to have allowed children to produce the compensatory forces necessary to minimise any perturbations to posture caused by their arm movements whilst tracking (Shadmehr and Brashers-Krug 1997; Kawato 1999; Krakauer et al. 1999; Burdet et al. 2006). The tracking task did generate a large amount of HM relative to the other tasks as might be expected from the need to maintain fixation on the moving target (as found previously in Experiment 1). The fact that the HMs were not associated with decreased postural stability supports our hypothesis that the synergistic dependency between HMs and posture is reduced when children are seated.

We used a standard school chair and this appeared to provide sufficient support to attenuate the large postural differences normally present in different age groups of primary-school-aged children. Whilst we have shown that it is possible to ameliorate the differences in postural control through the provision of seating in typically developing children, a standard school seat might not provide sufficient support for children with movement difficulties. A widely used intervention for children with cerebral palsy is to provide adaptive seating based on biomechanical and neurodevelopmental principles. This is predicated on the principle that improved postural control increases manual control (Case-Smith et al. 1989; Smith-Zuzovsky and Exner 2004; Chung et al. 2008). This raises the question of whether children with more subtle motor deficits (e.g. developmental coordination disorder) might also benefit from specialised seating. The apparatus and experimental approach described here allow this question to be addressed in future studies.

Conclusion

In the introduction to this paper, we suggested that childhood development does not follow a linear progression from unskilled to skilled behaviour. The nonlinear nature of the developmental progress can be seen within the data we collected. For example, in Experiment 1, the oldest group of children show clear improvements in their ability to maintain stable posture when visually tracking a target but have almost identical COP displacement in the manual-tracking task, compared to their younger counterparts. This pattern of results is consistent with the notion that different skills develop at different rates with progression in one skill often dependent on another skill improving first. The synergistic relationship between head, hand and postural control appears to provide a good model of this dynamic interdependency. In fact, the relationship is further complicated by the anatomical changes that occur over the developmental period meaning that the system needs to compensate for changes in mass, lever length, distribution of weight, etc. In Experiment 2, we demonstrated that the age effects expected to be found in posture whilst manipulating a stylus manually were absent when seated. Task-related differences in postural stability were noted though, and thus, we interpret this finding as suggestive of underlying age differences being attenuated through the additional support provided by a chair. In sum, postural stability was affected by the demands of the task above and beyond postural control development.

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