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RESEARCH ARTICLE

Postural control and head stability during natural gaze behaviour in 6- to 12-year-old children

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Abstract We investigated how the influence of natural exploratory gaze behaviour on postural control develops from childhood into adulthood. In a cross-sectional design, we compared four age groups: 6-, 9-, 12-year-olds and young adults. Two experimental trials were performed: quiet stance with a fixed gaze (*fixed*) and quiet stance with natural exploratory gaze behaviour (*exploratory*). The latter was elicited by having participants watch an animated short film on a large screen in front of them. 3D head rotations in space and centre of pressure (COP) excursions on the ground plane were measured. Across conditions, both head rotation and COP displacement decreased with increasing age. Head movement was greater in the *exploratory* condition in all age groups. In all children—but not in adults—COP displacement was markedly greater in the *exploratory* condition. Bivariate correlations across groups showed highly significant positive correlations between COP displacement in ML direction and head rotation in yaw, roll, and pitch in both conditions. The regularity of COP displacements did not show a clear developmental trend, which indicates that COP dynamics were qualitatively similar across age groups. Together, the results suggest that the contribution of head movement to eye-head saccades decreases with age and that head instability—in part resulting from such gaze-related head movements—is an important limiting factor in children's postural control. The lack of head stabilisation might particularly affect children in everyday activities in which both postural control and visual exploration are required.

Keywords Postural control · Children · Head stability · Gaze · Vision

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Introduction

'Simply' standing upright is in fact a challenging skill. This is reflected in the time it takes to acquire and optimise it. Adult-like postural control occurs only around the age of 12 (Ferber-Viart et al. 2007; Mallau et al. 2010; Peterson et al. 2006).

Why does postural control take so long to develop fully? Besides factors related to physical growth, different maturational explanations have been formulated. First, it is known that the cerebral cortex matures gradually during childhood years (O'Leary 1990) and that the cerebral cortex and higher cognitive functions contribute to postural control (Slobounov et al. 2009). Second and relatedly, although the sensory systems involved in postural control (i.e., visual, vestibular and somatosensory) are thought to be mature well before the age of 12, their functional integration might not be (Peterson et al. 2006). Third, the longer electromechanical delay and slower force development in children reported in Asai and Aoki (1996) constitute an immaturity of the muscular system that possibly affects children's postural control. Fourth, Mallau et al. (2010) reported immature segmental stabilisation in children as compared to adults. Particularly head-in-space stabilisation seems to take long to develop, whereby the age of 7 seems to present a turning-point towards adult-like behaviour in this respect (Assaiante and Amblard 1995).

Schärli et al. (2012), who specifically assessed the development of head rotation and postural sway during quiet stance, found that young children show both larger postural sway and larger head rotations than older children and adults. Both these differences were more prominent with than without gaze shifts. Based on these findings, they hypothesised that head rotations in space might be related to balance performance in children. In line with this hypothesis, it has been argued that head stability in space is a fundamental goal of the postural control system in adults (Menz et al. 2003b; Pozzo et al. 1990). Moreover, during complex equilibrium tasks such as standing on a narrow beam or on a rocking platform, head rotations are kept to a minimum and are considerably smaller than trunk rotations in healthy adults (Pozzo et al. 1995). Finally, increased head movement during postural disturbances has been shown to predict risks of falls in the elderly (Wu 2001), and poor head stability has been associated with falls in the elderly (Menz et al. 2003a).

How might head movement affect standing balance? First, the destabilising torques induced by head rotations especially in pitch (about the transverse axis) and roll [about the anterior-posterior (AP) axis] pose a mechanical challenge to the standing posture as they occur at the top of an inverted pendulum. Second and probably more importantly, head movement generates sensory input to the somatosensory (i.e., neck proprioception), vestibular and visual systems that is unrelated to postural changes and hence constitutes noise to the postural control system.

The previous paragraphs suggest that maximal postural stability requires minimal head movement. Yet head movement cannot simply be minimised because many everyday activities depend on our ability to move our heads (for visual exploration) and control our posture simultaneously. It would therefore be prudent to study postural control development under conditions in which large gaze shifts (i.e., gaze shifts necessarily involving head rotation) are required. Bonnet and Despretz (2012) found that adults increased their body sway during large lateral gaze shifts (i.e., visual angle of 150°) in standard and wide stance but did not do so during narrow and tandem stance. It thus seems that, in adults, gaze shifts involving head movement increase postural sway only if balance is not thereby challenged. Children's increased body sway with gaze shifts during narrow stance found by Schärli et al. (2012) suggests that in young children, postural sway involuntarily increases and hence—unlike in adults—might challenge their balance during narrow stance.

Schärli et al. (2012)—to the best of our knowledge the only study directly addressing the influence of visual exploration on postural control in children—examined the influence of gaze shifts on postural control in a rather artificial gaze shift paradigm: participants rhythmically shifted their gaze back and forth between two dots arranged either horizontally or vertically. Under such conditions, gaze shifts are monotonous and hence highly predictable, affording conscious deliberation as to the extent to which head movement should be involved. Schärli et al. (2012) also restricted the target range so that targets could theoretically be fixated without the need of concomitant head movements. In the present study, we examined whether the findings of Schärli et al. (2012) hold true in a more natural gazing situation, in which visual exploration is unpredictable and covers a larger range. Under such conditions, it was our aim to describe the magnitude of head rotations as well as the magnitude and regularity of centre-of-pressure (COP) movements in three children groups of increasing age and one group of young adults.

Methods

Participants

Seventy subjects without any known neurological, motor or ocular disorders participated in the study. They were recruited from a local primary school. The following four age groups were formed: 6-year-olds (mean age 6.2 ± 0.5 years, $n = 14$), 9-year-olds (mean age 8.7 ± 0.2 years, $n = 21$), 12-year-olds (mean age 11.7 ± 0.4 years, $n = 16$) and young adults between 18 and 35 years (mean age 28.9 ± 3.61 years, $n = 19$). All adult participants and the parents of the participating children gave their written informed consent and children their verbal consent prior to conducting the experiment. The experimental procedures were approved by the local ethics committee and performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

Vertical ground reaction forces were measured with a Kistler force plate (Type 9286B, Kistler, Winterthur, Switzerland), and three-dimensional head rotations—relative to an earth-fixed reference frame—were measured with the head-mounted marker frame of the Zebris CMS20S system (Zebris Medical GmbH, Isny, Germany). The measuring method is based on the travel time measurement of ultrasonic pulses transmitted by three head-mounted markers to the three microphones built into the measuring sensor. An animated short film (Saldanha 2002) was shown on a rear projection screen (width x height: 2.2 × 1.3 m), set up at a horizontal distance of 1.1 m from participants' toes

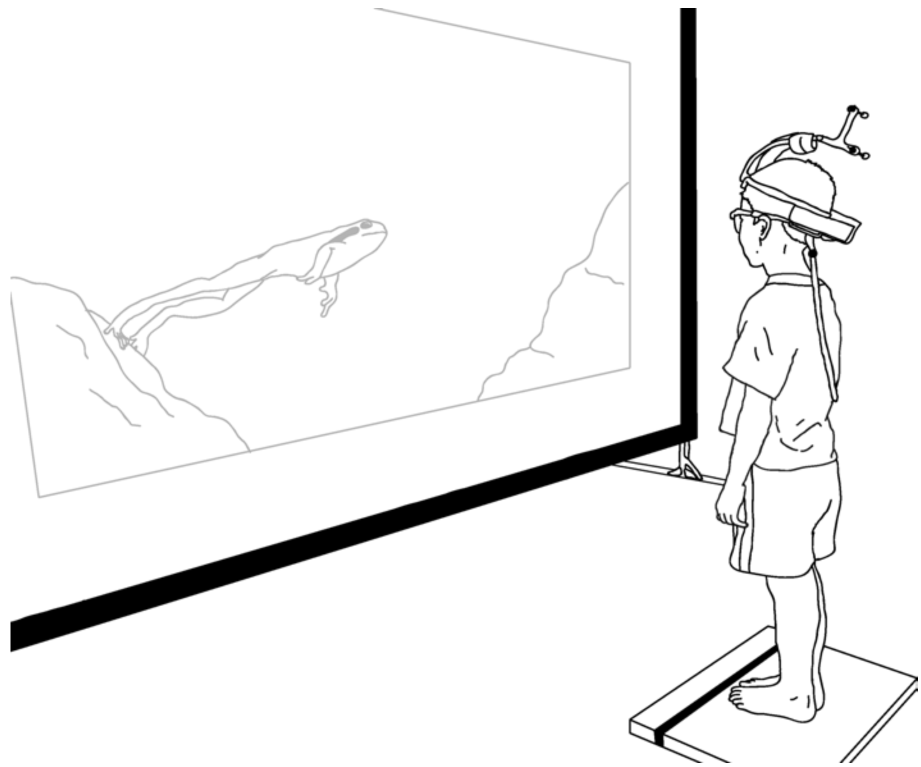

Fig. 1 Experimental set-up for both the fixed and exploratory gaze conditions. The screen (2.2 m width × 1.3 m height) was placed at eye height and subtended a visual angle of 90° *horizontally* and 61° *vertically*

(see Fig. 1) so that it subtends a visual angle of 90° horizontally and 61° vertically. The centre point of the screen was adjusted to participants' eye height. Furthermore, subjects were equipped with a mobile eye tracking system (Applied Science Laboratories, Bedford MA, USA). Eye movement data helped to ensure compliance with experimental tasks (e.g., to keep gaze fixed on a dot) and allowed the assessment of actual gaze direction in the exploratory condition.

Experimental procedure

Prior to the experiment, body height, eye height, weight and feet circumference of each participant were recorded. Then, participants stood quietly, heels and forefeet together, on the force platform in two conditions. First, a baseline measurement of 60 s was performed, in which participants simply gazed at a single coloured dot (diameter 5 cm) projected straight ahead at eye level (*fixed*). Second, participants were shown the 4.5-min animated film (Saldanha 2002), during which they were allowed unrestricted gaze behaviour (*exploratory*). The film featured action in all parts of the screen and prompted highly dynamic gaze behaviour in all participants. Instructions to all participants were to stand quietly on two feet (i.e., no movements with arm and legs) and fixate either the coloured dot or watch the movie freely as in a cinema. Data recording started once the participant stood quietly on the force plate. Data from participants who moved their gaze away from the fixation point in the fixed gaze condition or off the screen in the exploratory condition (as determined with the eye tracking equipment) were excluded for further analysis.

Data reduction

Vertical ground reaction forces (sampled at 1,000 Hz) and three-dimensional head rotations (i.e., head yaw (about the vertical axis), roll (about the AP axis) and pitch (about the transverse axis); sampled at 60 Hz) were recorded. The head rotation time series were linearly interpolated to match the length of the force time series. Then, force and head rotation time series were both down-sampled to 100 Hz and smoothed using a moving average window of 100 ms for further analysis. The first and last 3 s of the experimental trials were removed to ensure steady-state data.

COP displacements in AP and medio-lateral (ML) directions were obtained from the four recorded vertical forces on, and the moments around, the four force sensors of the plate. In order to quantify the magnitude of COP displacements, interquartile ranges (IQRs) of AP and ML COP displacements were calculated. As sway magnitude is scale-dependent, IQRs were normalised to base-of-support: for AP sway, IQR was divided by foot length, and for ML sway, IQR was divided by foot width (i.e., largest distance between lateral edges of left and right feet). In order to describe the regularity of COP displacements, sample entropy (SE) of both COP–AP and COP–ML time series (normalised to unit variance) was calculated by means of the software available at PhysioNet (Goldberger et al. 2000). Optimal values for tolerance range ($r = 0.05$) and template length ($m = 3$) were estimated according to Lake et al. (2002). The calculation of SE has gained popularity in the analysis of COP time series since its introduction by Richman and Moorman (2000), who found SE to be a better measure than approximate entropy in the study of experimental clinical cardiovascular and other biological time series. SE is an indicator for the regularity of COP trajectories. In a regular trajectory, one may predict the next data point with reasonable accuracy (low SE), whereas in an irregular trajectory, such a prediction is impossible (high SE).

Finally, as an indicator for the amount of head rotation, IQR of head rotation in yaw, roll and pitch directions was calculated for both experimental conditions.

Statistical analyses

As most of the data did not show a normal distribution, nonparametric statistics were adopted for all analyses. As a description of central tendency and variability of outcome measures, median with lower and upper quartiles (i.e., 25th and 75th ‰, respectively) was calculated. In order to pinpoint developmental changes, a full set of planned Mann–Whitney *U* tests was performed between the different age groups. Because these comparisons were non-orthogonal, Benjamini–Hochberg corrections were adopted (Waite and Campbell 2006). To compare the two conditions (i.e., fixed vs. exploratory) within age groups, Wilcoxon signed-rank tests were employed for the two COP outcome measures (i.e., IQR and SE) and the head rotations in yaw, roll and pitch direction.

Bivariate correlations were calculated between each of the COP displacement measures (in AP and ML directions) and each of the head rotation measures in yaw, roll and pitch. These correlations were calculated both across all participants and within each age group.

Significance level was set at 5 %. Effect size was calculated according to $r = \frac{Z}{\sqrt{N}}$ where Z is the approximation of the observed difference in terms of the standard normal distribution, and N is the total number of samples. $r = 0.1$ is considered a small, $r = 0.3$ a medium and $r = 0.5$ a large effect size.

Results

Results of the magnitude of head rotation, the magnitude and regularity of COP displacement are reported in separate subsections. In each subsection, between-group comparisons for both the fixed and exploratory gaze conditions are presented first, followed by within-group comparisons between fixed and exploratory gaze conditions. Correlations between the magnitude of head rotation and COP displacement are presented in a separate subsection.

Magnitude of head rotation

IQR of head yaw differed significantly in both conditions between 6- and 12-year-olds, between 6-year-olds and adults, between 9-year-olds and adults, and between 12-year-olds and adults (see Table 1). The younger group in each comparison showed larger head yaw (see Fig. 2a). Differences between 9- and 12-year-olds were not significant in both conditions. Head yaw did not differ significantly between 6- and 9-year-olds in the fixed gaze condition. Head roll differed significantly in both conditions between 6- and 12-year-olds, 6-year-olds and adults, between 9-year-olds and adults, and between 12-year-olds and adults (see Table 1). Six- and 9-year-olds, and 9- and 12-year-olds differed in the fixed gaze condition only. In each comparison, the younger group showed larger head roll movement (see Fig. 2b). Head pitch differed significantly in both conditions between 6- and 12-year-olds, between 6-year-olds and adults, between 9-year-olds and adults, and between 12-year-olds and adults (see Table 1). In the fixed condition, a significant difference for head pitch was detected between 9- and 12-year-olds. The younger group in each comparison showed larger head pitch movements (see Fig. 2c).

In our experiment, the angular range of the visual material (±45°) greatly exceeded the eye-only range, that is, the range of target eccentricity with respect to the head within which subjects are likely to fixate a new visual target without moving the head, a range averaging ±18° in normal adults (Stahl 1999). It is therefore not surprising that the exploratory gaze condition resulted in significantly larger head yaw, roll and pitch in all age groups (all p's ≤ 0.001).

Magnitude of COP displacement

IQR of COP displacement in ML direction in both the fixed and exploratory gaze conditions was statistically different between 6-year-olds and all other age groups, and between 9-year-olds and adults (see Table 2, second column). In both conditions, the younger group of each comparison showed higher values than the older group: their COP displacement in ML direction covered a larger portion of their base-of-support width (see Fig. 3a). Nine- and 12-year-olds differed significantly in the fixed gaze condition only and 12-year-olds and adults in the exploratory gaze condition. Differences between children groups and the adults for COP displacement in ML direction in the exploratory gaze

Table 1 Statistical outcome of the Mann–Whitney U comparisons for interquartile range of head rotation in yaw, roll and pitch

Group	Condition	Head yaw				Head roll				Head pitch			
		U	Z	p_{corr}	r	U	Z	p_{corr}	r	U	Z	p_{corr}	r
6 years versus 9 years ($n1 = 14$, $n2 = 21$)	Fixed	114	−1.396	0.20	0.24	54	−3.321	0.001	0.56	108	−1.588	0.117	0.27
	Exploratory	63	−2.828	0.004	0.48	88	−1.987	0.058	0.34	101	−1.549	0.152	0.26
6 years versus 12 years ($n1 = 14$, $n3 = 16$)	Fixed	43	−3.044	0.004	0.56	29	−3.597	<0.001	0.66	43	−3.044	0.004	0.56
	Exploratory	28	−3.492	<0.001	0.64	39	−3.035	0.003	0.55	55	−2.370	0.017	0.43
6 years versus adults ($n1 = 14$, $n4 = 19$)	Fixed	24	−4.110	<0.001	0.72	2	−4.873	<0.001	0.85	15	−4.422	<0.001	0.77
	Exploratory	7	−4.590	<0.001	0.80	3	−4.735	<0.001	0.82	19	−4.153	<0.001	0.72
9 years versus 12 years ($n2 = 21$, $n3 = 16$)	Fixed	120	−1.472	0.147	0.42	96	−2.207	0.027	0.36	99	−2.115	0.042	0.35
	Exploratory	153	−0.460	0.660	0.08	129	−1.196	0.241	0.20	145	−0.705	0.495	0.12
9 years versus adults ($n2 = 21$, $n4 = 19$)	Fixed	62	−3.724	<0.001	0.59	18	−4.916	<0.001	0.78	47	−4.130	<0.001	0.65
	Exploratory	56	−3.887	<0.001	0.61	26	−4.699	<0.001	0.74	87	−3.047	0.006	0.48
12 years versus adults ($n3 = 16$, $n4 = 19$)	Fixed	74	−2.583	0.01	0.44	45	−3.543	<0.001	0.60	64	−2.914	0.005	0.49
	Exploratory	57	−3.146	0.001	0.53	38	−3.775	<0.001	0.64	80	−2.384	0.034	0.40

condition were highly reliable (all p's < 0.001). Even in the oldest children, COP displacement in ML direction was still clearly larger than in adults.

IQR of COP displacement in AP direction in both the fixed and exploratory gaze conditions was significantly different between 6-year-olds and all other age groups (see Table 2, first column). A statistically significant difference of IQR of COP displacement in AP direction was further found between 9-year-olds and adults for the fixed gaze condition. In all comparisons, the younger group of each comparison showed higher values: their COP displacement in AP direction covered a larger portion of their base-of-support length (see Fig. 3b). No differences were found between 9- and 12-year-olds, between 12-year-olds and adults for both conditions, and between 9-year-olds and adults for the exploratory condition.

The exploratory as compared to the fixed gaze condition resulted in a significantly larger COP displacement in ML direction in all children age groups (6-year-olds: $Z = -2.605$, $p = 0.009$, $r = 0.70$; 9-year-olds: $Z = -2.800$, $p = 0.005$, $r = 0.63$; 12-year-olds: $Z = -3.181$, $p = 0.001$, $r = 0.82$). The group of adults did not show a significant difference between conditions ($Z = -1.590$, $p = 0.112$, $r = 0.37$). In AP direction, no significant differences were found between the fixed gaze and exploratory gaze condition in all age groups (6-year-olds: $Z = -0.596$, $p = 0.551$, $r = 0.16$; 9-year-olds: $Z = -0.747$, $p = 0.455$, $r = 0.17$; 12-year-olds: $Z = -1.761$, $p = 0.078$, $r = 0.45$; adults: $Z = -0.762$, $p = 0.446$, $r = 0.18$).

We compared COP displacement in the first and last minute of the exploratory condition in all age groups. No significant differences were found (except in the 6-year-olds, where ML sway slightly decreased). Hence, fatigue related to the larger trial duration in the exploratory condition is not responsible for differences in COP displacement between fixed and exploratory conditions.

Correlations between COP and head rotation magnitudes

Results of the correlations between each of the COP displacements (i.e., AP and ML directions) and all head rotations (i.e., yaw, roll and pitch directions) are presented in Table 3. Across participants and conditions, highly significant positive correlations of moderate strength were found between head rotation in all directions and COP ML displacement. Across participants in the fixed condition, a weak yet highly significant positive correlation was found between head roll and COP AP displacement. Within age groups, only two significant correlations of moderate strength were found: between head yaw rotation and COP ML displacement in the 6-year-olds and between head roll rotation and COP AP displacement in the 12-year-olds.

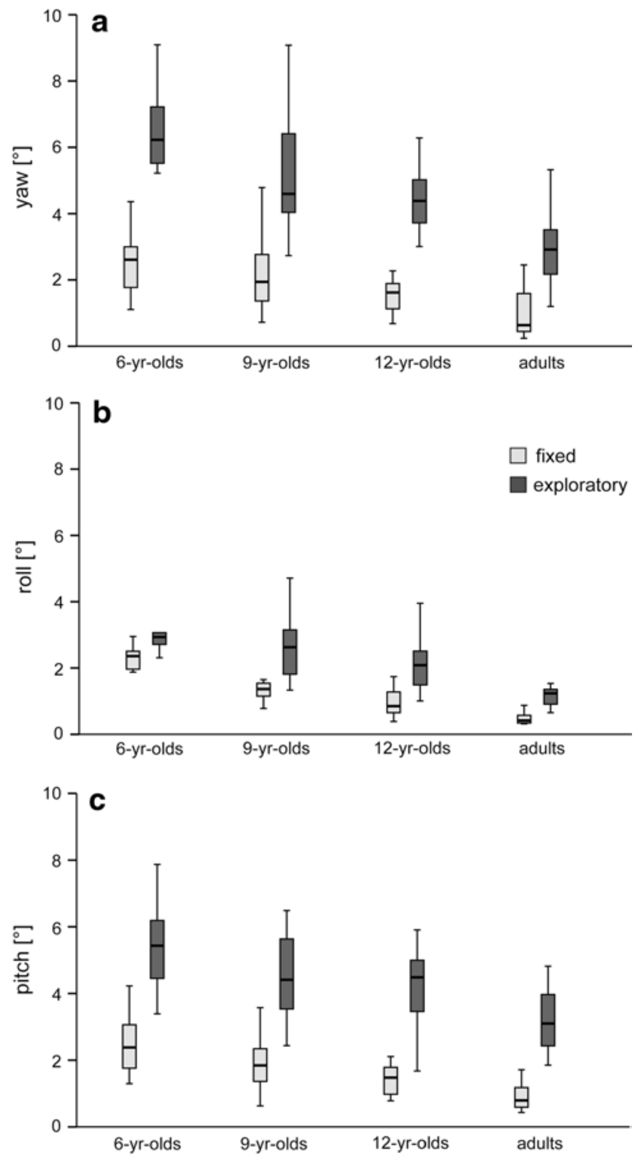

Fig. 2 *Box plots* featuring median, Q1 and Q3 with smallest and largest unbooked sample values shown as whiskers for IQR of head rotations in **a** yaw, **b** roll and **c** pitch directions for age group 6-, 9-, 12-year-olds, and adults. The first *box* per age group represents the fixed gaze condition, the second box the exploratory gaze condition

Furthermore, in the 9-year-olds in the exploratory condition, COP ML displacement showed moderately strong correlations with both head roll and pitch that approached significance (both p's between 0.05 and 0.1). The remaining correlations were not significant (all p's > 0.1).

Regularity of COP displacement

Regularity of COP displacement in AP and ML directions showed no clear differences between age groups in both the fixed and exploratory gaze conditions (see

Table 2 Statistical outcome of the Mann–Whitney *U* comparisons for interquartile range and sample entropy values of centre-of-pressure (COP) displacement in anterior-posterior and medio-lateral directions

Group	Condition	COP_AP_IQR				COP_ML_IQR				COP_AP_SE				COP_ML_SE			
		U	*Z*	p_{corr}	*r*	*U*	*Z*	p_{corr}	*r*	*U*	*Z*	p_{corr}	*r*	*U*	*Z*	p_{corr}	*r*
6 years versus 9 years (*n*1 = 14, *n*2 = 20)	Fixed	71	−2.41	0.03	0.41	47	−3.25	0.002	0.56	107	−1.16	0.39	0.20	113	−0.90	1.00	0.16
	Exploratory	51	−3.42	<0.001	0.59	60	−3.13	0.001	0.54	113	−1.43	0.19	0.24	120	−1.203	0.36	0.21
6 years versus 12 years (*n*1 = 14, *n*3 = 15)	Fixed	37	−2.97	0.01	0.55	16	−3.88	<0.001	0.72	99	−0.26	0.81	0.05	74	−1.35	1.00	0.25
	Exploratory	35	−3.22	0.002	0.60	19	−3.88	<0.001	0.72	96	−0.68	0.51	0.13	111	−0.06	0.97	0.01
6 years versus adults (*n*1 = 14, *n*4 = 18)	Fixed	37	−3.3	<0.001	0.60	21	−3.99	<0.001	0.71	81	−1.71	0.18	0.30	103	−0.87	0.080	0.15
	Exploratory	32	−3.724	<0.001	0.66	2	−4.81	<0.001	0.85	71	−2.31	0.06	0.41	88	−1.89	0.18	0.33
9 years versus 12 years (*n*2 = 20, *n*3 = 15)	Fixed	117	−1.10	0.38	0.19	82	−2.27	0.023	0.38	118	−1.07	0.36	0.18	146	−0.13	1.00	0.02
	Exploratory	153	−0.14	0.9	0.02	118	−1.27	0.21	0.21	100	−1.85	0.13	0.31	116	−1.33	0.38	0.23
9 years versus adults (*n*2 = 20, *n*4 = 18)	Fixed	104	−2.22	0.04	0.36	66	−3.33	0.001	0.54	75	−3.07	0.012	0.50	179	−0.03	0.99	0.00
	Exploratory	133	−1.58	0.18	0.26	31	−4.45	<0.001	0.72	57	−3.72	<0.001	0.60	174	−0.69	0.60	0.11
12 years versus adults (*n*3 = 15, *n*4 = 18)	Fixed	91	−1.59	0.14	0.28	97	−1.37	0.18	0.24	85	−1.81	0.22	0.31	129	−0.22	1.00	0.04
	Exploratory	103	−1.16	0.31	0.20	28	−3.87	<0.001	0.67	93	−1.52	0.20	0.26	85	−1.99	0.28	0.35

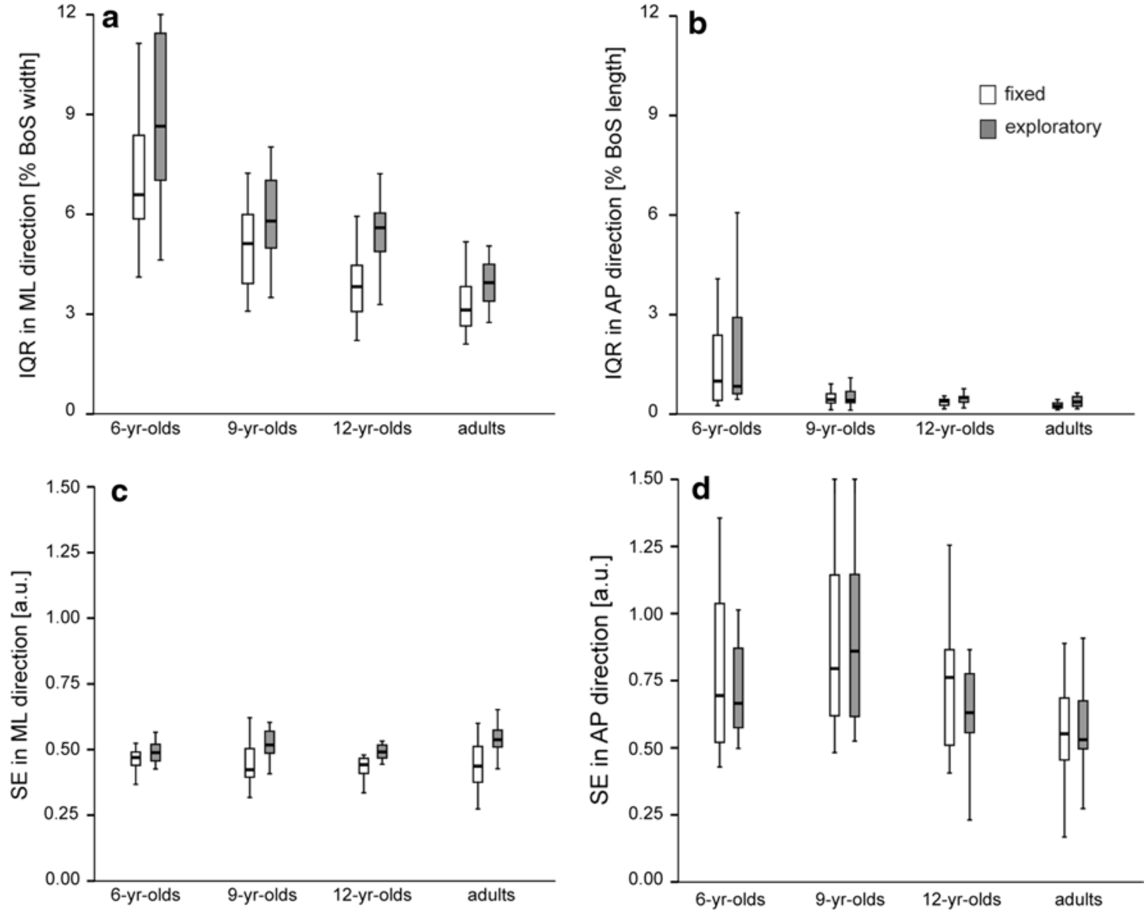

Fig. 3 *Box plots* featuring median, Q1 and Q3 with smallest and largest unbooked sample values for IQR of centre-of-pressure (COP) displacement in **a** medio-lateral and **b** anterior-posterior directions as well as for sample entropy values of COP displacement in **c** medio-lateral and **d** anterior-posterior directions for age group 6-, 9-, 12-year-olds, and adults. The *firstbox* per age group represents the fixed gaze condition, the *secondbox* the exploratory gaze condition. IQRs of COP displacement are an indicator of the magnitude of body sway, whereas sample entropy values stand for the regularity of COP displacement

Table 2). The only significant differences found were in AP direction in both conditions between the 9-year-olds and adults. The 9-year-olds showed lower regularity (i.e., higher SE) of COP displacement in AP direction than adults for the fixed and exploratory gaze conditions (see Fig. 3d). In ML direction, none of the age groups differed significantly with respect to regularity of COP displacement (see Table 2 and Fig. 3c).

Within age groups, no significant differences were found between conditions for the regularity of COP displacement in AP direction (6-year-olds: $p = 0.331$; 9-year-olds: $p = 0.478$; 12-year-olds: $p = 0.069$; adults: $p = 0.586$).

The exploratory as compared to the fixed gaze condition resulted in significantly lower regularity of COP displacement in ML direction in the 9-year-olds ($Z = -3.659$, $p < 0.001$, $r = 0.82$), 12-year-olds ($Z = -2.613$, $p = 0.009$, $r = 0.67$), and adults ($Z = -3.332$, $p = 0.001$, $r = 0.79$) but not in 6-year-olds ($p = 0.124$).

Discussion

In this cross-sectional study, we investigated how the influence of natural exploratory gaze behaviour on postural control develops from childhood into adulthood. Participants stood quietly on a force platform in two experimental conditions: a *fixed gaze* condition, in which they focused on a stationary target, and an *exploratory gaze* condition, in which they watched an animated movie. Comparison of the four age groups (6-, 9-, 12-year-olds, and young adults) revealed a clear developmental trend in both postural control and head-in-space rotation from the youngest to the oldest. Both head rotation and COP displacement clearly decreased with increasing age in both conditions. Regularity of COP displacement did not show a clear developmental trend, which indicates similar COP control across age groups.

The developmental trends in head stability and postural control were strikingly similar—a finding that suggests a

Table 3 Statistical outcome of bivariate Pearson's correlations between interquartile range (IQR) of centre-of-pressure (COP) displacement in anterior-posterior (AP)/medio-lateral (ML) directions and IQR of head rotations in yaw, roll and pitch directions, respectively

	6-year-olds	9-year-olds	12-year-olds	Adults	Across all
Fixed condition					
COP_AP—head_yaw					
r	−0.243	0.202	0.101	−0.305	0.028
p	0.403	0.394	0.719	0.219	0.821
COP_ML—head_yaw					
r	0.611	0.212	0.321	0.291	0.538
p	0.020	0.370	0.243	0.241	<0.001
COP_AP—head_roll					
r	0.327	−0.059	0.612	−0.095	0.330
p	0.191	0.805	0.015	0.709	0.006
COP_ML—head_roll					
r	−0.043	0.095	0.001	−0.044	0.428
p	0.883	0.691	0.997	0.861	<0.001
COP_AP—head_pitch					
r	−0.149	−0.134	0.356	−0.168	0.074
p	0.612	0.572	0.193	0.505	0.550
COP_ML—head_pitch					
r	0.227	0.293	0.047	−0.027	0.424
p	0.435	0.210	0.867	0.915	<0.001
Exploratory condition					
COP_AP—head_yaw					
r	−0.283	0.183	0.002	−0.117	0.139
p	0.327	0.427	0.995	0.645	0.260
COP_ML—head_yaw					
r	0.045	0.300	0.227	−0.225	0.549
p	0.879	0.186	0.416	0.369	<0.001
COP_AP—head_roll					
r	−0.261	0.355	−0.168	0.070	0.100
p	0.368	0.115	0.550	0.781	0.417
COP_ML—head_roll					
r	0.091	0.401	−0.017	−0.108	0.528
p	0.757	0.071	0.953	0.670	<0.001
COP_AP—head_pitch					
r	−0.318	0.250	−0.055	−0.301	0.049
p	0.268	0.274	0.847	0.225	0.691
COP_ML—head_pitch					
r	0.094	0.416	0.395	0.180	0.539
p	0.750	0.061	0.145	0.475	<0.001

connection between the two. In the remainder of this discussion, we will first discuss the development of head movement in gaze behaviour and then postural control development and the possible significance of head movement therein.

Magnitude of head rotation

Our main finding concerning head stability was the clear decrease in head rotation amplitude with increasing age, not only in the exploratory, but also in the fixed gaze condition. Clearly then, it is not—or at least not exclusively—a difference in gaze shifting strategy that explains the larger head rotations in younger children: they seem to have difficulty keeping their head stationary even when not looking around. Although this effect was most pronounced in the youngest age groups, there was still a marked difference in head rotation between 12-year-olds and adults. Below we will discuss three possible explanations for children's increased head rotation in the absence of visual exploration.

First, it might simply be a reflection of their increased body sway. That is, if the standing child is modelled as an inverted pendulum, the head simply sways—and hence rotates—with the rest of the body. More body sway would then directly imply more head rotation (in roll and pitch directions). Using the above-described inverted pendulum model, we estimated sway-related head roll and pitch: for pitch (respectively roll) rotation, we took COP displacement in AP (respectively ML) direction as an estimate of horizontal centre-of-mass displacement (A) and half the body height as an estimate of the distance between the support surface to the centre-of-mass along the body's longitudinal axis (C). The sway-related pitch (respectively roll) angle is then simply given by the inverse sine of A over C. Estimated as such, sway-related head rotation amounts to <1° in the youngest children, whereas actual head rotations were considerably larger (see Fig. 2). Sway-related head roll accounted for 0.9° in the 6-year-olds, 0.6° in the 9-year-olds, 0.5° in the 12-year-olds and 0.4° in adults. AP sway thus accounts for a small fraction of the observed head pitch in all age groups. ML sway accounts for about one-third of head roll in all children groups and for nearly all head roll in adults. Given these estimates of sway-related head rotation, it is unlikely that body sway accounts for a significant fraction of the difference in head rotation between children and adults.

Another possible explanation for this difference is related to the maturational aspects of intersegmental coordination during quiet stance. Mallau et al. (2010) suggested that children adopt an immature segmental stabilisation strategy. Segmental stabilisation involves the coordination of many joints and muscles and hence constitutes quite a formidable challenge for the motor control system. If, in children, joint angles below the head indeed show greater (non-compensatory) variability, the greater head rotations found in our study are only to be expected.

A third explanation for the larger head rotations in children is purely mechanical in nature and relates to the allometry in human growth: children, even 12-year-olds, simply have a larger, heavier head than adults, which arguably has a stronger tendency to instability.

In the exploratory gaze condition, the age-effect of head movement was amplified relative to the fixed gaze condition. A difference in the contribution of head rotations to combined eye-head saccades between children and adults forms the most likely explanation for this amplification. Note that, relative to the fixed gaze condition, head yaw increased more than head pitch and roll. This difference would not be expected if increased body sway is the primary cause of increased head rotation, because increased AP and ML body sway arguably induce head pitch and roll, respectively, rather than yaw. Although eye-head saccades probably involve pitch (vertical gaze shifts) as well as yaw (horizontal gaze shifts), it is not surprising that yaw showed a larger increase. First, monkeys have been shown to be more likely to couple head movements to horizontal than to vertical saccades (Crawford and Guitton 1997)—a finding that is likely to generalise to humans. Second, our short film's aspect ratio simply offered a larger horizontal than vertical field of view. Judging from Fig. 2a, the yaw increase in the exploratory condition was larger in children than in adults, which suggests that the contribution of head movement to gaze shifts was larger in children.

Increased head movement during saccades has been shown in infants (Regal et al. 1983) and children (Murray et al. 2007; Schärli et al. 2012). The reason for this distinct eye-head coordination in children might lie in an immaturity of central nervous structures. One group has argued that adult eye-head coordination is characterised by the ability to decouple head and eye control during gaze shifts (Oommen et al. 2004; Oommen and Stahl 2005; Thumser et al. 2010). The investigators speculate that the decoupling relies on inhibitory influences of frontal cerebral structures over a more primitive eye-head synergy, perhaps organised within brainstem structures. These inhibitory influences, like many frontal functions, are absent in the immature brain (Bunge et al. 2002). Possibly it is this decoupling of eye and head control that takes so long to develop and hence forms an explanation of the distinct gaze strategies of children and adults.

We now turn to an apparent discrepancy between the present results on head movement and those of Schärli et al. (2012). The latter found that adults hardly moved their heads at all while looking back and forth between two dots. In the present study, adults showed considerable head rotations during the exploratory gaze condition. We identified three possible reasons for this difference. First, gaze shifts in the present paradigm were larger than those in Schärli et al. (2012), where the required gaze shifts could be performed comfortably with the eyes only. Second, it has been shown that a lower target oscillation frequency provokes larger head rotations as compared to a higher frequency (Giveans et al. 2011). In the present experiment, gaze shifts were—on average—slower than the 0.8 Hz gaze shifts in Schärli et al. (2012). Third, Oommen et al. (2004) found that the duration of gaze fixations positively correlates with head movement tendency. Hence, the short gaze fixations in Schärli et al. (2012) could have rendered head movement tendency less likely compared to the present study, in which gaze fixations (e.g., on conspicuous happenings on the screen) were often longer. This final point again shows that findings obtained under artificial gaze shift conditions may not generalise to natural settings.

We conclude our discussion on the magnitude of head rotation with the acknowledgement of an important limitation of the present study: in strict accordance with our aim to investigate the relationship between (gaze-induced) head-in-space movement and postural stability, we only measured the movement of the head in 3D space and the movement of the COP over the support surface. We did not measure trunk and leg kinematics. Such measurements would have rendered a discussion of the possible factors underlying head rotation differences between children and adults much less speculative. Specifically, the measurement of head-on-trunk (i.e., neck) rotations would have allowed us to tease apart saccade-related from sway-related head movements, and the additional measurement of hip, knee and ankle joint rotations would have provided insight into intersegmental stabilisation. Future studies should perform such kinematic measurements in the present experimental paradigm, so that the sources of head-in-space rotations across developmental stages may be determined.

Magnitude of COP displacement and its correlations with head rotation

Turning now to a discussion of the observed differences in COP displacement between age groups, our results support findings of Ferber-Viart et al. (2007) and Mallau et al. (2010), who found that postural control is adult-like only beyond the age of 12. As discussed in the Introduction section, our results offer an explanation for this slow development of postural control in terms of head movement, both for the fixed and for the exploratory condition. Both Schärli et al. (2012) and the present study uncovered a parallel development of head stability and postural stability. The present results strongly suggest that this relationship is not merely spurious: participants performed identical balance tasks (standing quietly with feet together) in two visual conditions (fixed vs. exploratory gaze). In all children participants, the exploratory condition resulted in larger COP displacement, which strongly suggests that gaze shifts and the associated head rotations affected postural stability in children. In the group of adults, on the other hand, gaze shifts in the exploratory condition were not associated with a statistically significant increase in sway.

Although the absence of significant correlations between head rotation and COP displacement within age groups seems to suggest that no (causal) relationship between head rotation and COP displacement exists, a closer look at (1) the available range of head rotation and COP displacement within age groups and (2) the available number of samples within each age group leads to another likely explanation. The available ranges of the to-be-correlated variables as well as the available sample size are clearly smaller within than across age groups and together lead to a significant reduction in statistical power. It is therefore quite likely that a (causal) relationship between head movement and body sway exists, yet could not be shown statistically within age groups. This explanation in terms of statistical power is in line with the observed correlations between head rotation and COP displacement across groups, as well as the observed covariation of head rotation and COP displacement across conditions in the children groups. In order to more adequately test whether a non-spurious relationship between head movement and body sway is present, comparisons within age groups are indispensable. Yet the magnitude of head movement should be manipulated in a controlled manner so as to increase its range and hence to increase the likelihood of detecting a relationship, if indeed there is one. One experimental method by which this may be achieved is to have children—rather than simply gazing back and forth as in Schärli et al. (2012)—point a head-mounted laser pointer back and forth between two dots spaced increasingly far apart while standing on a force platform.

Regularity of COP displacement

The regularity of COP displacement did not show a clear developmental trend from early childhood into adulthood in both the fixed and exploratory gaze conditions. Hence, the present findings provide no suggestion of a difference in postural control strategy between age groups. Younger children might control their posture loosely relative to adults and therefore show larger sway, but the structure in COP displacements seems to be similar. This idea is in line with Bertenthal et al. (2000) who suggest that infant's postural control system is not fundamentally different from that of adults. Chen et al. (2008) provide further support for this invariance. They reported a decrease in sway magnitude in infants from walking onset to 9 months after walking, but no differences in sway dynamics expressed by SE. They thus suggested that the control principles develop first, followed by a 'mere' fine-tuning to minimise sway magnitude. With respect to the present study, this would suggest that the development of control principles was already complete even in our youngest age group and that the 'mere' fine-tuning of feedback loops seems to be incomplete even at the age of 12.

In the 9-, 12-year-olds, and adults, COP sway was less regular in the exploratory gaze condition than in the fixed gaze condition. This supports the attention hypothesis coined by Donker et al. (2007). These authors argue that sway regularity increases if attention is focused on postural control (e.g., standing with eyes closed) and decreases if attention is focused elsewhere (e.g., a cognitive dual task). Given that our exploratory condition may be deemed a cognitive (i.e., perceptual) dual task, the entropy increase in this condition may have been related to a decreased attentional focus on postural control.

In conclusion, our study demonstrates that head rotations during natural, exploratory gaze behaviour as well as during a fixed gaze decrease with increasing age and that this development goes together with an increase in postural stability. In the fixed gaze condition, head rotations are in part a reflection of body sway and hence point to immature segmental stabilisation in children. In the exploratory gaze condition, head yaw and pitch seemed to be related in large part to combined eye-head saccades and were markedly larger in children than in adults. In children, a different gaze strategy—one in which head movements are larger—seems to be an important cause of postural instability. In adults, visual exploration does not necessarily cause postural instability.

Our findings concern the relatively mundane task of standing quietly. A failure to stabilise the head may even be more disturbing when children face more challenging balance situations such as balancing on one leg and/or on uneven and irregular surfaces. In such situations, the inability to stabilise the head may even increase children's risk of falls. As the 'fine-tuning' of both head stability and postural stability seems to be so complex as to require more than 12 years to complete, there is a pressing need for future studies to probe further both these aspects of motor development, particularly their intriguing relationship.

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Conflict of interest The authors declare that they have no conflict of interest.

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