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Age-dependent adaptations to anticipated and non-anticipated perturbations after balance training in children

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Postural control undergoes rapid changes during child development. However, the influence of balance training (BT) on the compensation of perturbations has not yet been investigated in children. For this purpose, young (6.7 ± 0.6 years) and old children (12.0 ± 0.4 years) were exposed to externally induced anticipated (direction known) and non-anticipated (direction unknown) perturbations on a free swinging platform before and after either child-oriented BT (INT; young: n = 12, old: n = 18) or regular physical education (CON; young: n = 9, old: n = 9). At baseline, old children exhibited less platform sway after perturbations than young children ($p = .004$; $\eta_p^2 = 0.17$). However, no differences were found between anticipated and non-anticipated perturbations. After training, INT reduced the platform sway path while CON remained stable (−11.1% vs. +2.7%; $p < .001$; $\eta_p^2 = 0.26$). Furthermore, the young INT group adapted statistically similarly in anticipated and non-anticipated situations (−7.9% vs. −12.6%; $p = .556$; $r = 0.33$), whereas the old INT group tended to improve more in anticipated perturbations (−15.1% vs. −8.2%; $p = .052$; $r = 0.51$). Thus, the maturity of the postural system seems to influence the extent of training adaptations in anticipated perturbations. Furthermore, this study provides evidence that BT can improve postural responses to external perturbations in children and may represent a useful intervention to prevent falls.

1. Introduction

It was previously shown that children display a high risk of falling (Granacher, Muehlbauer, Gollhofer, Kressig, & Zahner, 2011) with negative consequences for health care costs (Kahl, Dortschy, & Ellsasser, 2007; Mathers & Penm, 1999; Moorin & Hendrie, 2008). Furthermore, the ability to counteract external perturbations was shown to predict the risk of falls in older adults (Sturnieks et al., 2013). It might therefore be assumed that the ability to compensate externally or internally induced postural perturbations is also essential for children to reduce the risk of falls; especially as the quality of such responses is considered to be low in young children (Westcott & Burtner, 2004). With respect to non-anticipated externally induced perturbations, it was shown that postural responses of children are maturing with age. After sudden toe-up rotations, the onset of the anterior tibialis muscle – which is not activated by a stretch reflex but essential to restore position in this movement – was demonstrated to decrease from the age of 14 months to the age of 15 years (Haas, Diener, Bacher, & Dichgans, 1986). Furthermore, the variability of postural responses after

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non-anticipated external perturbations was shown to be higher in children under the age of 7 when compared with older children or adults (Berger, Quintern, & Dietz, 1985; Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985; Woollacott, Debu, & Mowatt, 1987).

Regarding anticipated perturbations in children, most studies investigated the development of anticipatory postural adjustments (APA), which are characterized by feedforward activities in postural muscles already before the onset of a voluntary movement (e.g. arm rising). For instance, when children were asked to stand on tiptoe as soon as possible after an acoustic cue, the time needed to initialize the anticipatory forward shift (i.e. APA) decreased with age (Haas, Diener, Rapp, & Dichgans, 1989). Additionally, young children under the age of 8 years were shown to display inconsistent anticipatory patterns in comparison to older children when performing a self-initiated arm rising task (Hay & Redon, 2001; Riach & Hayes, 1990). This suggests that younger children have limited abilities to generate adequate APAs to self-induced perturbations when comparing with older children or adults.

On the other side, responses to externally induced anticipated perturbations were shown to be modulated based on the preparatory setting (or central set) in adults (Horak, Diener, & Nashner, 1989; Wälchli, Tokuno, Ruffieux, Keller, & Taube, 2017). The preparatory setting is defined as a neural readiness state based on the predictability of a stimulus and the generation of an adequate response to it (Smith, Jacobs, & Horak, 2012). There exists to our knowledge only one study which investigated the preparatory setting in children (Hay & Redon, 1999). In this study, children held a load in their horizontally outstretched arms. The load was removed either through a self-initiated release (anticipated) or externally lifted up (non-anticipated). Six to 8-year-olds showed highly variable responses and therefore a less efficient anticipatory strategy in the voluntary releasing task when compared with older children (9–10 years) and adults. The authors assumed that "…high-level anticipatory control and information-processing mechanisms… (Hay & Redon, 1999, p. 161)" are less matured in young children compared to older children or adults.

However, a design where anticipated and non-anticipated perturbations were both triggered externally to assess the preparatory setting – without any influence of APAs – has not yet been investigated in children. Therefore, the first aim of the present study was to analyze postural responses of children exposed to externally induced anticipated (prior knowledge about the direction) and non-anticipated perturbations (direction not previously known). We hypothesized that the older children (11–13 years) perform better than the younger children (6–7 years) in both, anticipated and non-anticipated perturbations. For this purpose, the overall ability to counteract perturbations, i.e. performances in all 4 directions together was analyzed in a first step. Subsequently, performances in the 4 directions were compared separately between the young and the old group to get a more detailed insight. Regarding the preparatory setting, postural sway was expected to be reduced in anticipated perturbations (i.e. previous information about the direction) when compared with non-anticipated perturbations.

Moreover, evidence is missing whether balance training (BT) can positively influence the postural responses to perturbations in children. Better postural responses to anticipated translational perturbations were previously reported in 13 year old adolescents after ice skating training (Keller, Röttger, & Taube, 2014) and in adults after classical BT (Taube et al., 2007). Furthermore, infants (36–40 weeks) improved the postural response pattern after platform perturbations when exposed to intense perturbation training (Sveistrup & Woollacott, 1997). Similar findings were reported for 20–40 weeks old infants in perturbed sitting balance, where postural response modulation increased after two months of toy reaching training (Hadders-Algra, Brogren, & Forssberg, 1996). However, BT-induced adaptations to perturbations with altered preparatory setting have never been investigated in children between 4 and 13 years of age. Therefore, the second aim of the present study was to evaluate the age-dependent trainability of anticipated and non-anticipated perturbations in children.

2. Methods

Parents and children were previously informed about the study protocol and gave their written consent. Ethical principles of the Helsinki Declaration were respected and the local ethics committee permitted the realization of the present study (87/14). Other parts of this study were published earlier (Wälchli, Ruffieux, Mouthon, Keller, & Taube, 2018).

2.1. Participants

Initially, 25 young (YOUNG) and 28 old children (OLD) without any motor difficulties started the experiment after parents had reported no neurological and/or orthopedic impairments for their participating children. An intervention (INT) and a control group (CON) were analyzed for both ages. The INT groups consisted of regular school classes and children of the CON groups attended other schools in the same region. Only 48 children could be taken into the final analysis due to leisure time injury (OLD-INT: 1) or incomplete data (YOUNG-INT: 3; YOUNG-CON: 1; see Table 1).

2.2. Perturbations

A two-dimensional free swinging platform (Posturomed, Haider, Bioswing, Pullenreuth, Germany) was used to assess postural stability after either anticipated (direction known) or non-anticipated (direction not known) postural perturbations in four different directions (anterior, posterior, left, right). Perturbation onset was induced manually by the experimenter and was entirely unpredictable for the participants. The tests were executed in double leg stance with feet together, arms akimbo and a natural head position while looking at a given point (Kapteyn et al., 1983). To induce a perturbation, the platform was moved away from its middle position by servomotors and was swinging freely after the release. Acceleration (2.15 m/s^2), peak velocity (0.22 m/s) and distance (2 cm) of the perturbations were kept constant throughout the experiment. A reflecting marker was placed on the platform

Table 1
Anthropometric data of the intervention (INT) and the control (CON) groups for both age groups (young and old).

	YOUNG		OLD	
	INT	CON	INT	CON
n	12	9	18	9
Gender [f/m]	7/5	4/5	7/11	4/5
Age [years]	6.5 ± 0.4	6.8 ± 0.8	12.0 ± 0.4	12.0 ± 0.5
Weight [kg]	22.3 ± 4.1	22.6 ± 3.6	47.9 ± 11.2	41.7 ± 4.6
Height [cm]	118.5 ± 6.3	123.8 ± 11.8	154.3 ± 5.7	152.3 ± 4.0

Note: Values for age, weight and height are indicated as group mean ± standard deviation. f = female. m = male.

and the movement of the marker was captured with a Vicon 512 System (Vicon Motion Systems Ltd., Oxford, UK). The movement of the marker represented the sway path of the platform and was analyzed offline in MatLab (Version 2014b, The MathWorks, Inc., Natick, MA). The overall sway path length of the platform was calculated as the mean of all trials in all four directions for both perturbation conditions separately (anticipated and non-anticipated, respectively). Postural performance of the children was assessed as the length of the platform sway path. For this purpose, the participants were instructed to minimize the platform sway during 6 s after the onset of the perturbation.

2.3. Procedure

Baseline performances were assessed in the week before the training started (PRE). For security reasons, all participants started with the anticipated perturbations. Three trials per direction were recorded [directions (4)*trials (3)]. Subsequently, 12 perturbations were applied without prior instruction about the perturbation direction (non-anticipated). The direction of perturbation occurred in a randomized order.

After PRE-measurements, the INT groups were exposed to child-oriented BT that lasted for five weeks with two sessions per week (45 min/session). The content and arrangement of the child-oriented BT was previously described in detail and was shown to improve unperturbed dynamic postural control and explosive strength (Wälchli et al., 2018). Briefly, the child-oriented BT contained a large variation of exercises with different difficulty levels to provide challenging tasks for every child at any time point of the training. However, our child-oriented BT did not include postural perturbations. Children of the CON groups followed regular physical education lessons (no specific BT exercises). The training duration and the number of training sessions were identical for the two groups. All participants repeated the perturbation testing procedure 3 to 7 days after the intervention ended (POST).

2.4. Statistics

Normal distribution was checked with Shapiro-Wilk tests. Overall baseline performance was analyzed using a 2 × 2 ANOVA with the factors AGE (YOUNG vs. OLD) and CONDITION (ANTICIPATED vs. NON-ANTICIPATED). Direction specific performance was subsequently analyzed with 2 separate 2 × 4 ANOVAS with the factors AGE and DIRECTION (ANTERIOR vs. POSTERIOR vs. LEFT vs. RIGHT) for the anticipated and the non-anticipated perturbations. The development from PRE to POST (i.e. BT-induced adaptations) is expressed as percentage difference from PRE to POST due to a high variability within groups and was analyzed using a 2 × 2 × 2 ANOVA with the factors GROUP (INT vs. CON), AGE, and CONDITION. If the threefold interaction revealed statistical significance, post hoc 2x2 ANOVAs were assessed to explain the threefold interaction. In case of statistically significant *F*-values of the two-way ANOVAs, Bonferroni corrected post hoc Student's *t*-tests were conducted. Effect sizes are presented as partial eta square values (η_p^2; small: 0.02; medium: 0.13; large: 0.26) for ANOVAs and as Pearson correlation coefficient (*r*; small: 0.10; medium: 0.30; large: 0.50) for *t*-tests. Statistical analyses were done with SPSS software (Version 23, IBM Corp., Armonk, NY) and the alpha level was set at 0.05. Values are indicated as mean ± standard error.

3. Results

3.1. Baseline performance

All data were normally distributed. Baseline postural performance (i.e. PRE), assessed as the overall platform sway path of the free swinging platform after the perturbations, was significantly smaller in old compared to young children (i.e., AGE; $F_{1,46} = 9.202$; $p = .004$; $\eta_p^2 = 0.17$; see Fig. 1 and Table 2). However, no effects were found for CONDITION ($F_{1,46} = 0.107$; $p = .745$; $\eta_p^2 < 0.01$) and for the AGE*CONDITION interaction ($F_{1,46} = 2.472$; $p = .123$; $\eta_p^2 = 0.05$). To get more information about the differences in baseline performance between the young and the old children (i.e. due to the main effect of AGE), the platform sway path was additionally analyzed in the 4 perturbation directions separately. Significant AGE*DIRECTION interactions were found for both, anticipated ($F_{1,138} = 10.901$; $p < .001$; $\eta_p^2 = 0.19$) and non-anticipated perturbations ($F_{1,138} = 10.571$; $p < .001$; $\eta_p^2 = 0.19$; see Fig. 2). Bonferroni corrected post hoc tests revealed differences between the age groups for the length of the platform sway path after perturbations in the posterior (anticipated: $p = .004$, $r = 0.41$; non-anticipated: $p < .001$, $r = 0.53$) and anterior direction

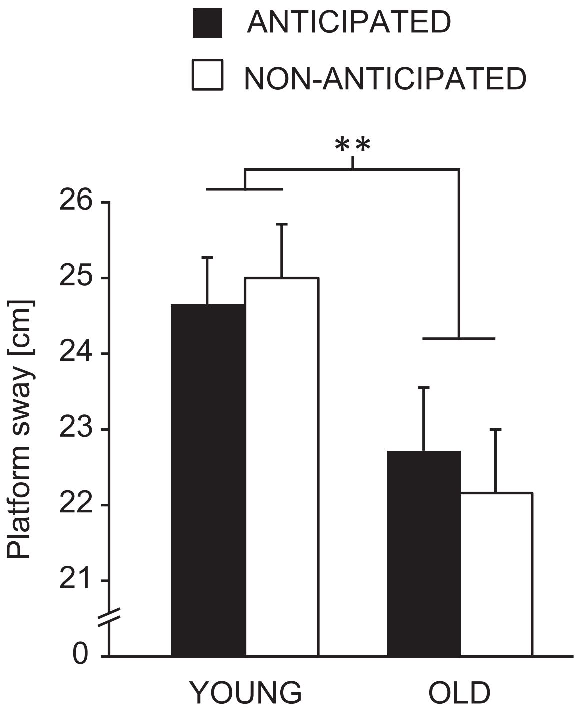

Fig. 1. Overall sway path (i.e. all 4 directions together) after perturbations on the free swinging platform in PRE measurements for young and old children. Black bars are representing perturbations where the direction is known (anticipated), whereas white bars representing perturbations without knowledge of direction (non-anticipated). $^{**}p < .01$.

Table 2
PRE measurement sway paths on the free swinging platform for both age groups (YOUNG and OLD) and adaptations from PRE to POST for both age groups separated into intervention (INT) and control (CON) group.

		Sway path PRE [in cm]		Adaptation from PRE to POST [in %]			
		YOUNG	OLD	YOUNG		OLD	
				INT	CON	INT	CON
Overall	A	24.65 ± 0.50	22.72 ± 0.53	−7.92 ± 2.78	1.00 ± 3.74	−15.08 ± 3.80	2.01 ± 4.03
	NA	25.00 ± 0.71	22.16 ± 0.57	−12.64 ± 3.99	4.65 ± 4.03	−8.18 ± 3.29	3.09 ± 2.25
Posterior	A	25.61 ± 0.82*	21.86 ± 0.90*	−7.75 ± 6.21	−0.01 ± 6.36	−16.20 ± 4.67	5.08 ± 4.00
	NA	25.69 ± 1.18*	21.04 ± 0.72*	−12.53 ± 8.11	5.81 ± 6.05	−3.81 ± 3.87	3.90 ± 4.96
Anterioir	A	26.49 ± 0.83*	21.14 ± 0.73*	−7.04 ± 7.45	−1.24 ± 7.55	−29.19 ± 5.52	−2.44 ± 6.83
	NA	26.10 ± 1.49*	19.48 ± 0.72*	−11.72 ± 5.65	−4.30 ± 4.00	−13.33 ± 3.46	1.37 ± 4.46
Left	A	23.80 ± 0.78	24.14 ± 0.73	−12.18 ± 5.84	0.74 ± 6.31	−6.46 ± 4.69	1.37 ± 5.01
	NA	23.83 ± 0.81	24.46 ± 0.71	−15.97 ± 3.85	6.89 ± 4.86	−10.23 ± 4.17	3.01 ± 3.85
Right	A	22.71 ± 0.75	23.75 ± 0.69	−4.70 ± 7.35	4.52 ± 6.96	−8.48 ± 5.05	3.32 ± 3.90
	NA	24.37 ± 1.16	23.66 ± 0.73	−10.35 ± 7.72	10.20 ± 6.28	−5.36 ± 3.51	4.08 ± 5.48

Note: Overall = all 4 direction together. A = anticipated perturbations where the direction is known. NA = non-anticipated perturbations where the direction is not known. * = $p < .05$ for the difference between YOUNG and OLD.

(anticipated: $p < .001$, $r = 0.57$; non-anticipated: $p < .001$, $r = 0.59$). In both directions and conditions, the older group exhibited less platform sway than the younger children (see Fig. 2 and Table 2). In contrast, the platform sway paths of the two age groups were not different after perturbations in the medio-lateral direction.

3.2. Training adaptations

The changes in the platform sway path length from PRE to POST are indicated in Table 2 as percentage of the baseline performance. When considering the overall platform sway path in all 4 directions, the 2x2x2 ANOVA revealed a statistically significant main effect of GROUP ($F_{1,44} = 15.525$; $p < .001$; $\eta_p^2 = 0.26$) indicating that adaptations of INT groups were significantly different to

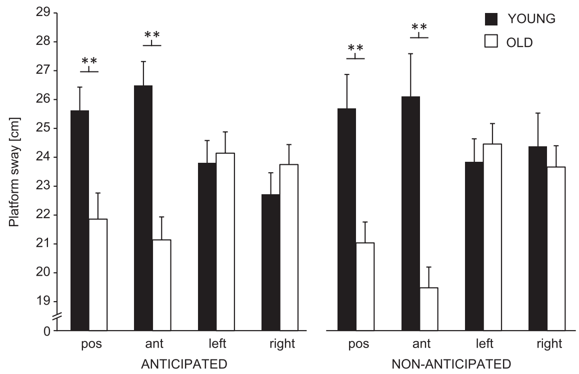

Fig. 2. Sway path after perturbations on the free swinging platform for each of the 4 directions in PRE measurements for young and old children. Black bars are representing sway paths of the younger children, whereas white bars representing sway paths of the older children. pos: posterior. ant: anterior. **p < .01.

adaptations of the CON groups (see Fig. 3). More importantly, a significant GROUP*AGE*CONDITION interaction was revealed ($F_{1,44}$ = 4.248; p = .045; η_p^2 = 0.09; see Fig. 3). However, no interaction effects were present for GROUP*AGE ($F_{1,44}$ = 0.024; p = .878; η_p^2 < 0.01), for GROUP*CONDITION ($F_{1,44}$ = 0.137; p = .713; η_p^2 < 0.01), and for AGE*CONDITION ($F_{1,44}$ = 1.732; p = .195; η_p^2 = 0.04).

Based on the large main effect of GROUP, two independent 2x2 post hoc ANOVAs were assessed for both the INT and CON groups in order to explain the threefold interaction. A significant AGE*CONDITION interaction was detected for the INT groups ($F_{1,28}$ = 5.794; p = .023; η_p^2 = 0.17) but not for the CON groups ($F_{1,16}$ = 0.441; p = .516; η_p^2 = 0.03). This finding suggests that the threefold interaction was caused by different adaptations within INT and CON groups. Therefore, subsequent Bonferroni corrected post hoc Student's *t*-tests for the INT groups were performed. Adaptions of platform sway path between the two perturbation conditions in YOUNG-INT did statistically not differ (p = .556; r = 0.33), whereas OLD-INT tend to improved more in the anticipated than in the non-anticipated condition (p = .052; r = 0.51; see Fig. 2). Comparisons between YOUNG-INT and OLD-INT revealed no differences in adaptations between anticipated (p = .360; r = 0.25) and non-anticipated postural responses (p = .792; r = 0.16).

As we did not find significant differences between the changes in the overall platform sway path in YOUNG-INT and OLD-INT, the changes in platform sway were additionally examined in each of the 4 directions separately (see Fig. 4 and Table 2). The adaptations of the YOUNG-INT group were consistent over directions in both, anticipated and non-anticipated perturbations (see Fig. 4). The older training group, however, decreased the sway of the platform in the anticipated condition considerably more in the anterior-posterior direction than in the medio-lateral direction. For instance, all 18 participants of the OLD-INT group could decrease the platform sway path in anticipated anterior perturbations and 5 participants were even able to reduce the platform sway path by more than 50%. In contrast, 3 out of 12 participants in the YOUNG-INT group exhibited more platform sway in the POST test and only one participant showed improvements above 50%.

4. Discussion

The aims of the present study were to evaluate 1) age-specific performance after anticipated and non-anticipated perturbations and 2) the influence of BT on postural responses in children of two different age groups.

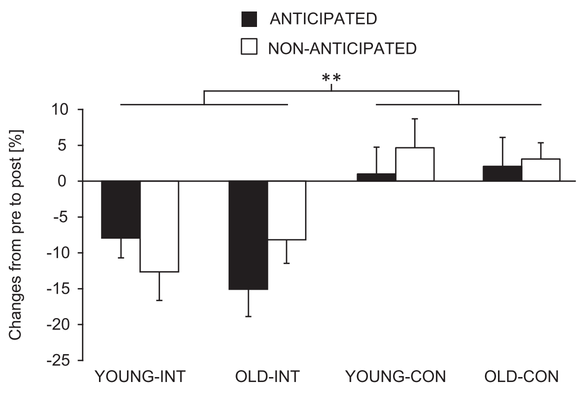

Fig. 3. Changes from PRE to POST test of the overall sway path (i.e. all 4 directions together) after perturbations on the free swinging platform. Black bars are representing perturbations where the direction is known (anticipated), whereas white bars representing perturbations without knowledge of direction (non-anticipated). INT: children exposed to balance training. CON: children attending regular physical education. **p < .01.

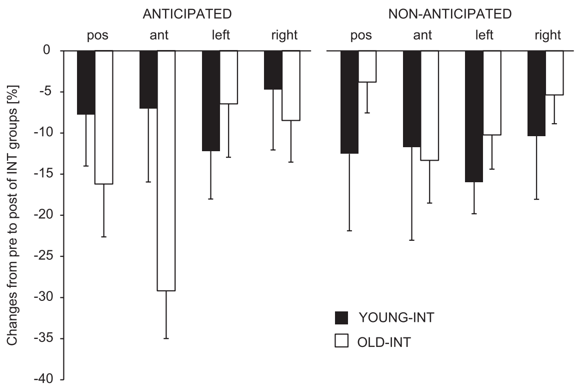

Fig. 4. Changes from PRE to POST test of the sway path after perturbations on the free swinging platform for each of the 4 perturbation directions. Black bars are representing performances of the intervention group of the younger children (YOUNG-INT), whereas white bars representing performances of the intervention group of the older children (OLD-INT). pos: posterior. ant: anterior.

4.1. Baseline performance

Externally induced perturbations leaded to smaller sway paths of the free swinging platform for old than for young children in anticipated and non-anticipated perturbations (see Fig. 1). This finding is in line with existing literature showing that responses to postural perturbations are maturing with age (Westcott & Burtner, 2004). Due to the fact that the old children performed better than the young children in both, the anticipated and the non-anticipated condition, we concluded that the postural control system to counteract perturbations was more matured in the older children. When analyzing the PRE performance in a direction specific way, the older group outperformed the younger group in the anterior and in the posterior direction whereas platform sway paths in the medio-lateral plane were statistically not different. It was previously hypothesized that medio-lateral sway in static stance requires different compensatory strategies than in the anterior-posterior plane (Winter, Prince, Frank, Powell, & Zabjek, 1996). The sway in the anterior-posterior plane was thought to be compensated by an ankle strategy while lateral sway is controlled by a hip strategy. However, responses to perturbations were reported to be more related between the two planes because the hip is also involved when counteracting perturbations in the anterior-posterior plane (Henry, Fung, & Horak, 1998). Compensating perturbations is based on loading/unloading of the rear/fore foot in the anterior-posterior plane and of the left/right foot for the lateral plane. As the younger children showed inferior performances in the anterior-posterior direction than the older children, it is suggested that the ability of the 6–7 year-olds to load/unload the required part of the foot is less matured than in 11–13 year old children. In contrast, it seems that there is no age-specific difference in the ability to counteract perturbations in the medio-lateral plane. In this regard, it was previously shown that the responses to posterior perturbations are related to the risk of falls in older adults (Sturnieks et al., 2013). Although such findings have not yet been reported for children, it can be assumed that younger children exhibit a higher risk of falls in perturbed situations because they have lower skills to counteract perturbations in the anterior-posterior direction.

In addition, no differences in platform sway between anticipated and non-anticipated perturbations were detected within age groups. Previous work demonstrated reduced peak amplitudes of the center of pressure (COP) in children after anticipated self-initiated perturbations (i.e. unloading task) compared to externally induced non-anticipated perturbations (Hay & Redon, 1999). The present study, however, exposed for the first time children to a test design where both, anticipated and non-anticipated perturbations were triggered externally to assess the influence of the preparatory setting. In adults, compensatory sway and muscular activity were shown to be appropriately tuned when perturbations could be anticipated (Horak et al., 1989). It might therefore be assumed that the children of both age groups do not (yet) possess the ability to adequately alter their preparatory setting when responding to external perturbations at baseline, i.e. before participating at a specific BT.

4.2. Training adaptations

Children exposed to child-oriented BT improved postural responses to anticipated and non-anticipated perturbations, demonstrating for the first time a transfer of balance skills to an untrained perturbation task in young children. This finding further indicates that the child-oriented BT positively affected postural control and is in line with previous findings where child-oriented BT improved dynamic unperturbed postural control and explosive force (Wälchli et al., 2018). As it was demonstrated that responses in the posterior direction were associated with the risk of falls in older adults (Sturnieks et al., 2013), it is suggested that also children can reduce their risk of falls with improved postural responses to perturbations. Therefore, it is assumed that child-oriented BT provides an effective means to reduce the amount of falls in children and consequently, also decrease health care costs during childhood.

Enhanced postural stability after BT was found for overall anticipated and non-anticipated perturbations in YOUNG-INT and OLD-INT (see Fig. 3). Participants from YOUNG-INT adapted to a greater extent (but not statistically significantly) in non-anticipated compared to anticipated perturbations. The reason for this more pronounced performance gain in non-anticipated perturbations may originate from the study design. Due to security reasons, the anticipated perturbations were always assessed first. This "nonrandomized" schedule might bias our results. As the task was new to the participants and not trained during the intervention, the YOUNG-INT group may have benefited more from a learning effect than from the information about the direction in the POST test. In contrast, children of the OLD-INT group achieved greater overall training gains in anticipated than in non-anticipated responses. The improvements in the anticipated condition were mainly caused by large adaptations after perturbations in the anterior and posterior direction (see Fig. 4). Interestingly, the older group could adapt even more than the young group in the anterior-posterior plane despite having had smaller sway paths in these two directions in the PRE test. When considering that responses to perturbations in the anterior-posterior direction are requiring optimal load distribution of the forefoot and rear foot (Henry et al., 1998), it can be assumed that the older group already exhibited a more mature loading control in the anterior-posterior direction (i.e., performance in PRE), which could be further improved by the child-oriented BT in anticipated perturbations. In contrast, performance after medio-lateral perturbations was similar in the PRE measurement between OLD-INT and YOUNG-INT and both age groups exhibited comparable extents of adaptations. Therefore, it can be speculated that the control of responses to perturbations in the medio-lateral direction is either matured already at the age of 6 years or that the main adaptation in this direction is occurring after the age of 13 years.

Concerning the different adaptations between anticipated and non-anticipated perturbations of the OLD-INT group, it was previously demonstrated that a transition phase from a predominantly reactive control towards an appropriate coordination between anticipatory and reactive control is taking place at the age of around 7 years (Hay & Redon, 1999; Shumway-Cook & Woollacott, 1985). In this context, it was shown that 6 to 8-year-olds exhibited an inefficient behavior (i.e. overcontrol) in self-induced perturbations (Hay & Redon, 1999). The authors concluded that appropriate postural responses to anticipated perturbations require optimal coordination of anticipatory and reactive control. Based on the fact that the YOUNG-INT group improved to a similar extent in anticipated and non-anticipated perturbations, it could be assumed that the young children did not yet have the ability to sufficiently integrate anticipatory knowledge, which may have prevented larger adaptions in anticipated situations. In contrast, the old children reduced their sway path more in anticipated perturbations than in non-anticipated perturbations and therefore differentiated between purely reactive and anticipatory control strategies after the child-oriented BT. Thus, the older children learned to profit from prior knowledge about the perturbation. This view is reinforced when looking at the data of the anticipated perturbations in the anterior-posterior direction, where the older group performed better in PRE and, nevertheless, adapted to a larger extent than the younger group.

Moreover, evidence is rising that supraspinal systems are playing a crucial role in the handling of postural perturbations (Bolton, 2015; Taube, Gruber, & Gollhofer, 2008) and that there are differences in cortical activity between anticipated and non-anticipated perturbations (Adkin, Quant, Maki, & McIlroy, 2006; Wälchli et al., 2017). Since it is known that the supraspinal system progresses during childhood (Giedd et al., 1999; Maatta et al., 2017) and showing adult-like behavior not until the age of 10 years (Bawa, 1981), the more mature supraspinal control may also positively influence training adaptations in anticipated perturbations in the older group.

5. Limitations

The findings of the present study are solely based on behavioral data (i.e. platform sway path) as it was not possible to investigate the underlying mechanisms with neurophysiological methods due to higher ethical regulations for children. Although studies with neurophysiologic measurements demonstrated differences between anticipated and non-anticipated perturbations in adults (Adkin et al., 2006; Mochizuki, Boe, Marlin, & McIlroy, 2010), it is still not clear whether the mechanisms in (young) children are similar to those of adults or not. Furthermore, the inclusion of an adult group would have provided more information about the postural response performance of the children. It was previously reported that an adult-like postural control is achieved from about the age of 12 years (Barozzi et al., 2014; Peterson, Christou, & Rosengren, 2006), but this cannot be confirmed for the OLD group in the present study as an adult group was not examined. Furthermore, a complete analysis of the full body movement after the perturbation may provide more information about the behavioral responses of the children than only the sway path of the free swinging platform. In addition, a larger sample size would enhance the power of the study and reinforce the outcome; especially for the differences between anticipated and non-anticipated perturbations.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2018.04.006.

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