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Development of Postural Control during Gait in Typically Developing Children: The Effects of Dual-task Conditions

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Abstract

The purpose of this study was to investigate the typical development of postural control in younger (5–6 yrs) and older (7–16 yrs) children (YTD and OTD) during two gait tasks, including level walking and obstacle-crossing, using a dual-task paradigm, and to compare the results of the children's performance with that of healthy young adults (HYA). Our findings revealed that gait control in typical children requires attentional resources to maintain stability. Moreover, dual-task interference was less in HYA compared to YTD and OTD. Gait performance decrements in the dual-task context were greater in YTD compared to OTD, whereas cognitive performance decrements in YTD and OTD were similar. In addition, dual-tasking affected cognitive performance more in YTD when gait task difficulty was increased. Results suggest a developmental trend in attentional resources used to control gait in typical children. Postural control during gait under dual-task conditions was improved when children were more mature, as attentional resources increased with age.

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Conflict of interest statement

The Authors declare that there is no conflict of interest.

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1. Introduction

Gait control has traditionally been considered an automatic function, requiring minimal cognitive processing. However, recent research has provided evidence indicating that gait requires attentional resources [1–5]. Research studying attentional resources required for postural control has typically used a dual-task paradigm [6]. In addition, few studies in gait control have explored the ability of children to perform both gait and a secondary cognitive task simultaneously [4,5]. These studies have demonstrated that walking while performing a cognitive task caused reductions in gait velocity, cadence and stride-length, and increases in double-limb support time and base-of-support [4,5]. However, these studies have not shown developmental trends for gait control in children, as only one group of children was included.

It has been demonstrated that different types of postural tasks require varying amounts of attentional resources, with more difficult tasks requiring increased attention resources [1,2,7]. It is reasonable to expect that maintaining dynamic balance during obstacle-crossing may be more challenging than level walking. A greater and faster motion of body segments while negotiating obstacles may result in a greater and faster movement of the center of mass (COM) and perturb balance [8,9]. Recent research in healthy young adults (HYA) has shown that obstacle-crossing requires more attentional resources than sitting or level walking [7].

The amount of dual-task interference varies depending on the age of the child and the type of secondary cognitive task [1,4,10,11]. One component of attentional processing, executive function, reaches near maturity at about 10 years of age, with the greatest changes in attentional function occurring at 6–8 years [12]. In order to study if interference due to information processing capacity limitations is the primary factor contributing to performance deficits in dual-task contexts, it is important to choose tasks that do not introduce structural interference [13]. Thus, recent studies used the auditory Stroop task, a test of executive attention, as a secondary cognitive task when examining obstacle avoidance under dual-task conditions [7,14]. In the present study, the auditory Stroop task was also used as a secondary task.

Research on typical children has examined both single and dual-task requirements of anticipatory postural control during locomotion. Children aged 7–9 years have reached adult-like control in their strategies to avoid obstacles [15]. Moreover, the ability to allocate attention in stance postural control is mature by age 7 [16]. It has also been shown that reweighting of sensory inputs under different environmental conditions was also mature by 7–10 years. Thus immaturity of the postural control systems, possibly associated with increased attentional requirements, may contribute to postural-cognitive task interference in younger children (4–6 yrs), as compared to older children and adults [16].

Previous research has neither explored the influence of cognitive tasks or the effect of task difficulty on postural control during gait in children. Therefore, the purpose of this study was to investigate the development of postural control during gait under dual-task conditions by comparing younger typical children (YTD) aged 5–6 years and older typical children (OTD) aged 7–16 years, with HYA aged 19–26 years [7]. We hypothesized that, 1) when compared with HYA, YTD and OTD would show greater interference between gait and cognitive task performance while performing walking and a secondary task, the auditory Stroop task; and 2) dual-task interference between gait and cognitive task performance in YTD would be greater than in OTD, especially in a more challenging gait task (e.g., obstacle-crossing).

2. Methods

2.1 Participants

Two groups of **twenty** typical children participated in the study: 20 YTD aged 5–6 years (9 females/11 males; age=6.22±0.63 years) and 20 OTD aged 7–16 years (9 females/11 males; age=10.92±2.95 years). Children had no known neuromuscular diseases or attentional deficits according to parents' and teachers' reports. Prior to entering the study, informed consent approved by the Human Subjects Compliance Committee of the University of Oregon, was obtained from the children and parents/guardians.

Children were assessed for motor function using the Gross Motor Function Measure (GMFM-88) [17] dimension D (standing) and dimension E (walking, running & jumping) and the Pediatric Balance Scale (PBS) [18]. In addition, a children's version of the Attentional Network Test (ANT) [19] was used to test children's attentional abilities.

2.2 Equipment

An eight-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) (sample rate, 60 Hz and fourth-order Butterworth filter with cutoff frequency of 8 Hz) was used to capture three-dimensional marker trajectories.

An obstacle (10% of body height) was placed in the middle of the 8-meter walkway for the obstacle-crossing task. The auditory Stroop task stimulus occurred during single limb support while crossing the obstacle. Stimuli were relayed to children through two speakers facing the walkway. The stimuli which were presented to children included the word “high” or “low” spoken with a high or low pitch. Congruency between pitch and the word was randomized. Children were asked to indicate the pitch of the voice as quickly and accurately as possible by saying “high” or “low” while ignoring the actual word presented [7].

2.3 Procedures

Children were asked to perform the following tasks: Three blocks of 4 trials of the auditory Stroop task (4-stimuli) in sitting (at the beginning and the end of the testing, and also between blocks of level walking and obstacle-crossing tasks). In each block of gait tasks, children were asked to perform 12 trials of level walking and obstacle-crossing in isolation, and another 12 trials of these tasks with auditory Stroop task (1-stimulus).

To counterbalance for fatigue and learning effects, half the children were asked to first perform a block of walking followed by a block of obstacle-crossing. The others were asked to perform the alternative sequence of tasks. The pilot study showed no effect of trial order. Children were instructed to walk at their preferred speed and wore a safety harness to prevent injury from an accidental fall. Practice trials for each task were given before collecting data. Children completed 48 total trials of the gait task and were allowed to rest if they became fatigued.

2.4 Data Processing and Analysis

Fifteen-body segment masses were estimated by using Jensen's formula [20] for 4–14 years of age and Winter's formula [21] for 15–16 years of age. These segment masses were used to compute the whole-body COM [21]. The COM range of motion and peak linear velocities in the sagittal plane (AP ROM and AP V, respectively) and coronal plane (ML ROM and ML V, respectively) during the crossing stride were used to quantify the child's dynamic stability while walking and obstacle-crossing. Temporal-spatial gait parameters, including gait velocity, stride-length, stride-time, and average step width, were also calculated during the crossing stride. All measures from the gait task for each testing condition were

normalized by subject's height or anterior superior iliac spine width to eliminate the effect of body size [22].

For the auditory Stroop task, verbal reaction time (VRT) of correct responses and percentage of correct responses were calculated. VRT was the time difference between onset of the stimulus and onset of the verbal response.

Gait and cognitive performance changes from single to dual-task conditions were calculated in proportional dual-task costs. Positive values indicate performance decrements whereas negatives values indicate performance improvements from single- to dual-task [23].

Statistical analyses were performed with SPSS v.16 (SPSS inc., Chicago, IL). Differences in baseline gross motor function, balance and attentional abilities obtained from PBS, GMFM, and ANT subsystems scores between YTD and OTD were determined by using independent t-tests. Children's gait and cognitive performance in the present study was compared with 12 HYA from a previous study, performed under the same conditions [7]. Main effects and interaction effects of the independent factors on gait were determined by a three-way mixed factorial ANOVA with weighted mean; group (YTD, OTD and HYA) $\times$ task (level walking and obstacle-crossing) $\times$ condition (single- and dual-tasks). A two-way mixed factorial ANOVA with weighted mean was applied to examine main effects and interaction effects of independent factors on VRT and accuracy; group (YTD, OTD and HYA) $\times$ condition (single and dual (walking), and dual (obstacle-crossing)). Group was a between-subject factor and task and condition were within-subject factors. Pairwise comparisons were carried out using Bonferroni corrections to identify direction of gait and cognitive performance changes. Dual-task costs were examined using planned comparisons.

3. Results

3.1 Baseline Characteristics (Table 1)

OTD showed significantly higher performance scores for the GMFM dimension E compared to YTD ($t(38) = 2.430$, $p = 0.020$). In contrast, balance abilities, as tested by the PBS and gross motor function skills in standing tested by GMFM dimension D were not significantly different ($p > 0.05$) between OTD and YTD. For the attentional network test, OTD showed better performance scores than YTD for attentional orienting ($t(38) = -2.098$, $p = 0.043$) and ignoring conflicting stimuli ($t(38) = -2.188$, $p = 0.035$). In contrast, attentional alerting scores were similar for both groups ($p > 0.05$).

3.2 Dual-task Effects on Gait Performance

Significant group $\times$ condition interactions were found for gait velocity ($F(2, 49) = 4.82$, $p = 0.01$, $\eta^2 = 0.16$), stride-time ($F(2, 49) = 4.25$, $p = 0.02$, $\eta^2 = 0.15$), and stride-length ($F(2, 49) = 4.76$, $p = 0.01$, $\eta^2 = 0.16$). YTD used a slower gait velocity with longer stride-time and shorter stride-length ($p < 0.001$) when simultaneously performing gait tasks and an auditory Stroop task. Decreased stride-length was also found in OTD under dual-task conditions (Figure 1).

3.3 Dual-task Effects on Gait Stability

Significant group $\times$ condition interactions were found for AP ROM ($F(2, 49) = 4.53$, $p = 0.02$, $\eta^2 = 0.16$), and AP V ($F(2, 49) = 4.20$, $p = 0.02$, $\eta^2 = 0.15$). YTD reduced AP ROM and AP V ($p < 0.001$) when concurrently performing gait tasks and an auditory Stroop task. Decreased AP ROM ($p = 0.02$) was also found in OTD when performing in dual-task contexts. In contrast to children, HYA did not show changes in COM displacement or linear velocity in the sagittal or coronal planes.

A significant task $\times$ condition interaction was found for AP V ($F(1, 49)=4.65$, $p=0.04$, $\eta^2=0.09$). Dual-tasking also induced a reduction in AP V in the level walking task ($p<0.001$), but not in obstacle-crossing (Figure 2).

3.4 Auditory Stroop Task Performance

There was a group main effect for VRT ($F(2, 49)=29.72$, $p<0.001$, $\eta^2=0.55$) and accuracy ($F(2, 49)=14.96$, $p<0.001$, $\eta^2=0.38$). YTD showed slower VRT and less accuracy than OTD and HYA ($p<0.001$). Significant condition effects ($F(2, 98)=3.98$, $p=0.02$, $\eta^2=0.08$) were also found for accuracy. Pairwise comparisons indicated accuracy was higher in single task than dual-task conditions ($p<0.05$). There was no significant difference in accuracy between the two dual-task conditions ($p>0.05$) (Figure 3).

3.5 Dual-task Costs

For gait stability, planned comparisons showed that, across all groups, dual-task costs for AP V were less in obstacle-crossing task than in level walking ($p=0.03$). YTD showed greater dual-task costs than HYA and OTD for AP V ($p<0.05$) in level walking and obstacle-crossing (Figure 3). Greater dual-task costs for AP ROM ($p<0.05$) in obstacle-crossing were also found in YTD as compared to HYA and OTD. Moreover, YTD had greater dual-task costs than HYA for AP ROM ($p<0.05$) in level walking (Figure 4a) and greater ML V ($p<0.05$) than OTD in obstacle-crossing (Figure 4b).

For gait performance, YTD showed greater dual-task costs than HYA and OTD for gait velocity and stride-time ($p<0.05$) in level walking and obstacle-crossing tasks (Figure 3). Greater dual-task costs for stride-length ($p<0.01$) in the obstacle-crossing task were also found in YTD compared to HYA and OTD. Moreover, YTD had greater dual-task costs than HYA for stride-length in level walking (Figure 4a).

There was no difference in dual-task costs for VRT between groups and between tasks. For accuracy, OTD showed greater dual-task costs than HYA in the level walking and obstacle-crossing tasks ($p<0.05$) whereas YTD showed greater dual-task costs than HYA only in obstacle-crossing ($p=0.05$). Dual-task costs were not different among groups for other measures in both level walking and obstacle-crossing tasks ($p>0.05$) (Figure 4).

4. Discussion

The present study examined the effect of dual-tasking on gait performance among YTD, OTD and HYA. Our findings revealed that dual-task interference with gait performance was greater in YTD and OTD as compared with HYA. In addition, gait performance decrements under dual-task contexts were greater in YTD than OTD. Moreover, the results supported our hypotheses that dual-task interference would be lowest in HYA and highest in YTD when compared among the three groups, particularly when crossing an obstacle. In addition, dual-task interference with gait performance in YTD was greater than OTD, suggesting a developmental trend in attentional resources required to control gait in typical children.

Results were consistent with previous studies exploring dual-task control in children, in showing that gait control in typical children requires attentional resources to maintain stability [4,5]. Huang et al (2003) examined dual-task effects on gait in children aged 5–7.8 years by using a visual, an auditory and a memorization task as the secondary cognitive task. Results showed a decrease in gait velocity for all concurrent cognitive tasks. In particular, the simultaneous performance of walking and either visual or auditory tasks decreased cadence and step length [4]. Additionally, Chéng et al (2007) reported that decreased gait velocity and stride-length, and increased double support time and base-of-support were

found in children 4–6 years of age when they were simultaneously walking and performing a secondary cognitive task, including repeating a numbers series forwards or backwards [5].

In the present study, gait stability, which has rarely been measured in developmental studies, was investigated. Interestingly, the results showed that ML ROM and ML Velocity were not affected by dual-tasking. Since balance loss during walking mostly occurs in the ML plane, it is possible that YTD and OTD maintained their gait stability by constraint of the COM displacement and velocity in the coronal plane, while using a strategy of changing the other gait characteristics in the dual-task context. These results are similar to those of a study by Schaefer et al (2008) on stance balance performance in dual-task situations. They found that children aged 9–10 years reduced sway when concurrently balancing on an ankle-disc board and performing a cognitive task, including working memory and episodic memory tasks. The authors suggested that children tried to maintain stability within narrow margins to protect themselves from falling in dual-task situations [23].

Moreover, in the difficult gait task, the information processing in YTD may be more in series, and thus more immature, than OTD and HYA, as YTD possibly performed one task at a time (Figure 5) to minimize the risk of falls when dual-tasking. YTD responded to the auditory Stroop stimulus after they stepped over an obstacle and took a few additional steps, whereas OTD responded to the stimulus shortly after they finished crossing the obstacle. In contrast to children, HYA performed obstacle-crossing and responding to the auditory Stroop stimulus at about the same time, suggesting that information processing for the two tasks in HYA could be largely performed in parallel. Previous research on brain processing mechanisms during dual-task contexts suggests that most dual-task brain processing (including sensory, parietal, pre-motor, supplementary motor and cerebellar areas) is in parallel in young adults, with serial processing limited to a parieto-prefrontal network [24]. It is possible that the parallel processing networks are not as efficient in children as adults and thus parallel processing is less evident within their brain systems.

In addition, across all groups, dual-tasking affected gait and cognitive performance while walking on a level surface as well as stepping over an obstacle. However, gait was less affected than cognitive performance, when the difficulty of the gait task increased. It is possible that this was due to all age groups prioritizing gait stability to prevent falling while stepping over the obstacle. Gage et al (2003) have suggested that in high risk tasks that could lead to balance loss, instability, or fear of falling, the allocation of attention was altered to enhance awareness of the current challenges to stability [25].

5. Limitations of this study

A limitation of the study was that the same cognitive task was used across all developmental levels. Thus it is hard to determine if the extent of the influence of the cognitive task would have been less pronounced if an age-equivalent cognitive task had been used. To minimize the effect of the difficulty of the cognitive task on age, YTD who demonstrated some difficulty in understanding the task or felt uncomfortable with its difficulty level were given more practice with the Stroop task accompanied by their parents' assistance until they understood and felt comfortable with the task.

In conclusion, our findings showed that YTD, who have not reached maturity with relation to gait and cognitive performance, demonstrated the greatest dual-task interference with gait postural control as compared with OTD and HYA. This study provides clinicians and teachers with information on age-related changes in gait and cognitive ability and how they affect a child's ability to perform cognitive and motor tasks simultaneously.

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Figure 1.

Gait performance variables; normalized gait velocity (A), stride-time (B), stride-length (C), and step width (D) for level walking and obstacle-crossing tasks under single and dual-task conditions in younger and older children with typical development (YTD and OTD) and in healthy young adults (HYA). *Significant difference between single- and dual-task conditions or level walking and obstacle-crossing tasks within group. #Significant difference between groups. **Significant difference between level walking and obstacle-crossing tasks across groups and conditions. †Significant difference between single- and dual-task conditions across groups and tasks.

Figure 2.

Gait stability variables; normalized center of mass (COM) range of motion in **(A)** anterior-posterior plane (AP ROM) and in **(B)** medial-lateral plane (ML ROM), and normalized peak linear velocity of the center of mass in **(C)** anterior-posterior plane (AP V), and in **(D)** medial-lateral plane (ML V) for level walking and obstacle-crossing tasks under single and dual-task conditions in younger and older children with typical development (YTD and OTD) and in healthy young adults (HYA). *Significant difference between single and dual-task conditions or level walking and obstacle-crossing tasks within group. #Significant difference between groups. **Significant difference between level walking and obstacle-crossing tasks across groups and conditions. ‡Significant difference between single and dual-task conditions in the level walking task across groups.

Figure 3.

Verbal reaction time (ms) (A) and accuracy (%) (B) for younger and older typically developing children (YTD and OTD) and healthy young adults (HYA) in single conditions (Single) and two dual-task conditions including level walking (Wk-Dual) and obstacle-crossing (Obs-Dual). *Significant difference between single and dual-task conditions. #Significant difference between groups.

A)

B)

Figure 4.

Dual-task cost for normalized gait measures (GV = gait velocity, ST = stride-time, SL = stride-length, SW = step width, AP ROM = anterior-posterior range of motion, ML ROM = medial-lateral range of motion, AP V = peak anterior-posterior linear velocity, ML V = peak medial-lateral linear velocity, verbal reaction time (VRT) and accuracy in younger and older typically developing children (YTD and OTD) and in healthy young adults (HYA) during level walking (A) and obstacle-crossing (B). *Significant difference between YTD and OTD. #Significant difference between YTD and HYA. \$Significant difference between OTD and HYA.

Figure 5. Example pictures of obstacle-crossing with a concurrent auditory Stroop task in healthy young adults (A), younger and older typically developing children (B and C, respectively), demonstrating the differences in the information processing (**differences between the onset of stimulus and response signals**) among groups.

Means (SE) of gross motor function ability, balance ability, and cognitive function ability in younger (YTD) and older children with typical development (OTD).

Table 1

Group	PBS	GMFEM		ANT		
		D	E*	Orienting*	Alerting	Conflicts*
OTD	56.00 (0.00)	39.00 (0.00)	72.00 (0.00)	18.70 (10.46)	69.68 (13.20)	56.05 (9.62)
YTD	55.50 (0.11)	38.70 (0.15)	71.20 (0.33)	56.70 (14.79)	49.68 (15.75)	98.45 (16.82)

PBS = Pediatric Balance Scale, GMFEM = Gross Motor Functional Measure, D = dimension D (standing), E = dimension E (walking, running and jumping), ANT = Attentional Network Test,

* significant difference at $p < 0.05$.