DEVELOPMENT OF POSTURAL CONTROL DURING GAIT IN TYPICALLY DEVELOPING CHILDREN AND CHILDREN WITH CEREBRAL PALSY: THE EFFECTS OF DUAL TASK CONDITIONS

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The purpose of this dissertation was (1) to investigate the effects of dual task conditions on the development of postural control during gait in typically developing children while walking and obstacle crossing, and (2) to investigate the attentional requirements of gait in children with cerebral palsy (CP). Forty younger and older typically developing (YTD and OTD) children and 10 children with CP performed a gait task with and without a concurrently auditory Stroop task. Gait and cognitive performance were measured.

In study 1, dual task interference with gait performance was found in YTD and OTD children, but not in healthy young adults (HYA). In general, gait performance decrements under dual task contexts were greater in YTD than OTD children, whereas

cognitive performance decrements during dual tasking were not different between the two groups of children. Dual task interference was lowest in HYA and highest in YTD children when compared among groups. As the difficulty of the gait task was increased, dual task affects on cognitive performance were now found in YTD and OTD children, but not HYA.

In study 2, there were significant differences in dual task interference affecting gait performance in all groups of children. When performing the gait task with a concurrent auditory Stroop task, OTD children showed greater dual-task costs than children with CP for accuracy, but children with CP demonstrated greater dual-task costs than OTD and YTD children for medial Center of Mass-Ankle-joint-center inclination angle. This increased medio-lateral inclination angle in dual task situations has also been seen in older adults with balance deficits and may be associated with an increased risk for falls. YTD children showed dual-task costs in a slowing of gait velocity and stride time, a safer strategy than that used by children with CP. The lower cognitive performance during dual tasking for OTD children suggests that they allocate greater attention to maintain gait stability, whereas YTD children and children with CP do not. In addition, children with CP use a behavior that may increase their risk of falls in complex environments.

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CHAPTER I

INTRODUCTION

One of the important problems occurring in children with cerebral palsy (CP) related to the delayed acquisition of motor skills is poor balance control (Woollacott & Shumway-Cook, 2005). Previous research has shown that stance balance control is reduced and loss of balance increases in children with CP and other balance-impaired individuals when they simultaneously perform a second cognitive task (Brown, Shumway-Cook, & Woollacott, 1999; Hyndman, Ashburn, Yardley, & Stack, 2006; Marchese, Bove, & Abbruzzese, 2003; Reilly, Woollacott, van Donkelaar, & Saavedra, 2008). Since falls very often occur while simultaneously balancing or walking and performing a second task such as engaging in conversation or carrying an object, this is a critical new research area (Connell & Wolf, 1997; Verghese et al., 2002; Verghese et al., 2007).

The process of learning to stand and walk involves the mastery of a number of motor skills, including dynamic balance and gait, and also integrating these tasks with other attentionally demanding tasks, such as carrying objects, communicating with others, and navigating in a visually complex environment. Research has shown that there are high rates of falls in typically developing infants and toddlers as they learn these motorically and attentionally demanding tasks (Joh & Adolph, 2006); in addition, studies have revealed that falls occurring while walking are one cause of unintentional injury in this young population (Britton, 2005). In children with CP balance and gait are impaired and thus coordinating these activities with other motor and cognitive tasks may require additional attentional resources beyond those required of typically developing (TD) children. Though falls and injury statistics are unavailable for this population, it is likely that, for these reasons, unintentional injury due to falls is even higher in children with CP who can walk than in the typically developing population. Research on balance control has shown that neuromuscular deficits are one factor contributing to falls in balance impaired populations. However, recent studies have shown that a second factor contributing to falls is a limitation in attentional resources required for coordinating both balance and secondary cognitive tasks simultaneously (Woollacott & Shumway-Cook, 2002). Falls often occur when not attending to balance while simultaneously performing a second cognitive task. It has thus been hypothesized that most falls are not due to balance deficits in isolation, but to the inability to effectively allocate attention to complex balance tasks or to balance in multitask conditions. It has also been hypothesized that interference between balance and secondary task performance may be apparent in classroom settings, with children with CP showing poor attention to classroom interactions because attentional resources are partially invested in focus on their own stability (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008; Reilly, Woollacott, van Donkelaar, & Saavedra, 2008).

Though there is no research yet available on falls incidence in children with CP, research indicates that many individuals have moderate to severe balance impairments that may require additional attentional resources during stance and mobility tasks. In children with CP, problems with balance control during gait often lead caregivers to recommend wheel chairs for ambulation, reducing daily exercise time for the child and thus reducing health status further (Andersson & Mattsson, 2001; Bennett et al., 2005; Bottos, Feliciangeli, Sciuto, Gericke, & Vianello, 2001; Bottos & Gericke, 2003; Sandstrom, Alinder, & Oberg, 2004).

Postural Control during Stance in Children with Cerebral Palsy

Previous research has explored the contributions of altered biomechanics, impairments in neural control and impairments in cognitive function to decreased balance and increased risk of falls in children with CP (Burtner, Qualls, & Woollacott, 1998; Burtner, Woollacott, Craft, & Roncesvalles, 2007; Burtner, Woollacott, & Qualls, 1999; Nashner, Shumway-Cook, & Marin, 1983; Reilly, Woollacott, van Donkelaar, & Saavedra, 2008; Woollacott et al., 1998). Somatosensory factors contributing to poor balance and falls include reduced ability to organize sensory information and to resolve intersensory conflicts (Cherng, Su, Chen, & Kuan, 1999; Nashner, Shumway-Cook, & Marin, 1983).

In one study examining the ability of children with CP to recover from slow velocity threats to balance (creating 20 deg/sec sway), children with spastic hemiplegia and diplegia showed a disruption in the normal distal to proximal muscle response organization, with proximal muscles typically being activated first. Some of the children with diplegia also showed a loss of directional specificity in the response organization. In conditions of increasing velocities and amplitudes of threats to balance, children with spastic diplegia showed temporal reversals among the muscles responding to loss of balance, in addition to high levels of agonist/antagonist muscle co-activation and they also did not increase response amplitudes and thus time to stabilize balance was larger than for TD children (Burtner, Woollacott, Craft, & Roncesvalles, 2007; J. Chen & Woollacott, 2007; Roncesvalles, Woollacott, & Burtner, 2002; Rose et al., 2002). In an effort to determine the contributions of musculoskeletal constraints to abnormal muscle response organization, researchers (Woollacott & Burtner, 1996) asked TD children to stand in a crouched stance similar to that of the children with spastic diplegia. This change in alignment made responses of the TD children more clearly approximate the onset latencies and organization of the children with spastic diplegia. This suggests that both neural and mechanical constraints contribute to abnormal muscle response organization in these children.

Studies have also shown that children with CP may have attentional limitations. For example it has been shown that many children with diplegic CP have limitations in their attentional processing abilities, as indicated by a reduced ability to inhibit responses to irrelevant stimuli when performing a task (Christ, White, Brunstrom, & Abrams, 2003). Additionally, children with CP may also have a smaller working memory capacity than TD peers (Reilly, Woollacott, van Donkelaar, & Saavedra, 2008). Additional research with the same group of children used a dual task paradigm to determine the effect of performing an attentionally demanding task on postural performance levels. The study has shown that children with CP had decreased balance control compared to their TD peers when they performed a standing task and a cognitive task (visual working memory task) synchronously (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008). Thus, the studies suggested that an impairment of cognitive function contributed to poor balance control in children with CP.

Postural Control during Gait in Children with Cerebral Palsy

The above research has emphasized testing balance during quiet stance and has concluded that children with CP showed significantly higher levels of sway or center of pressure (COP) movement than TD peers (Cherng, Su, Chen, & Kuan, 1999; Nashner, Shumway-Cook, & Marin, 1983; Rose et al., 2002). Though this research has provided information on stance balance control in these children, the reality is that most falls occur under the dynamic balance conditions of gait. Information about balance control during quiet stance is informative, but balance control requirements are increased during locomotion. Compared with standing, locomotion is more difficult because approximately 80% of the gait cycle is spent in single limb support. In addition, the center of mass (COM) is already in motion and has momentum that must be maintained or slowed, depending on the direction of the fall. Additionally, the strength required to manage the momentum changes caused by a quantity of body motion (momentum) becomes an even more critical consideration. Moreover, recovery of balance when locomotion is perturbed, for example by a slip, is significantly more difficult when compared to recovery from a similar threat during quiet stance.

The differences in balance and gait task difficulty are exaggerated in children with CP, due to their neural and musculoskeletal constraints contributing to balance dyscontrol. For example, biomechanical factors contributing to reduced balance during gait include reduced ankle, knee and hip range of motion, contributing to a crouched posture for gait, toe stepping and shorter step length (Norlin & Odenrick, 1986; Skrotzky, 1983; Wren, Rethlefsen, & Kay, 2005). Reduced ability to produce and modulate motor unit recruitment during walking (paretic component) also contributes to decreased balance performance (Rose & McGill, 2005).

Gait Maturation

Gait characteristics in TD children have also been investigated by many researchers (Chester, Tingley, & Biden, 2006; Dusing & Thorpe, 2007). Dusing and Torpe (2007) found that normalized gait velocity, step and stride length increased dramatically from children aged 1 year to 4 years. In contrast, cadence slightly decreased with age (Dusing & Thorpe, 2007). Chester et al (2006) also reported that there was decreased cadence and increased gait velocity in older children (7 years or older) compared with younger children (3-4 years) (Chester, Tingley, & Biden, 2006). According to Farmer (2003) maturation of gait occurs at about 7 years of age. Moreover, the normalized COM displacement in vertical and lateral direction appered to be unchanged when children were older than 4 years and in forward direction when they were beyond 7 years (Dierick, Lefebvre, van den Hecke, & Detrembleur, 2004). In addition, developmental research for anticipatory postural control during locomotion has shown that children aged 7-9 years have demonstrated adult-like proactive control in their strategies to avoid obstacles (McFadyen, Malouin, & Dumas, 2001).

Perturbed Locomotion

The inclusion of an obstacle course in many conventional clinical assessments has been demonstrated to be a useful tool in the evaluation of patients with balance and mobility impairment (Means, 1996; Means, Rodell, & O'Sullivan, 1996; Rubenstein et al., 1997). When stepping over an obstacle, the longer swing time required for the swing limb implies a longer duration of single stance for the supporting limb (Chou & Draganich, 1997; Patla & Rietdyk, 1993). Imbalance of the whole body during obstacle crossing may cause inappropriate movement of the lower extremities or striking an obstacle with the swing foot, and result in a fall. Greater and faster motion of body segments while negotiating an obstacle will result in greater and faster movement of the COM and perturb balance maintenance. Therefore, proper control of the COM motion and its coordination with the COP of the stance foot is important for the maintenance of the dynamic stability of the whole body when stepping over obstacles.

It is reasonable to expect that maintaining dynamic balance of the whole body during obstacle crossing may be a more challenging task than during unobstructed level walking. Studies have shown that there are significant differences between normal subjects and balance impaired patients in the medial-lateral (ML) motion of the COM during obstacle crossing, with patients with balance impairment showing significantly greater and faster ML motion of the COM (Chou, Kaufman, Brey, & Draganich, 2001;

Chou, Kaufman, Hahn, & Brey, 2003). These results indicate that differences in the ML COM motion between unobstructed level walking and during obstacle crossing may be used as functional indicators to identify children with immature and mature postural control during gait.

Attentional Resource Requirements for Postural Control

Though research on constraints on reactive and proactive balance control in children with CP has contributed to our understanding of one intrinsic factor contributing to falls, that of stability, recent research suggests that a second very important intrinsic factor contributing to poor balance during gait is impairment in cognitive processes, including attentional processing deficits. For example, research suggests that many falls in patients with balance impairment occur not when they are simply walking, but when they are walking and simultaneously performing a secondary task (such as talking or manipulating an object) (Bond & Morris, 2000; Faulkner et al., 2007). It has thus been hypothesized that these falls are not due to balance deficits in isolation, but to the inability to effectively allocate attention to balance in multi-task conditions (Lajoie, Teasdale, Bard, & Fleury, 1993; Reilly, van Donkelaar, Saavedra, & Woollacott, 2008; Reilly, Woollacott, van Donkelaar, & Saavedra, 2008; Anne Shumway-Cook & Woollacott, 2006). A growing body of research on attentional demands and posture suggests that the requirement for attentional resources varies as a function of three factors, postural task, age, and balance abilities.

Attentional Demands Vary as a Function of Postural Task

Though postural control and gait were traditionally considered to be automatic (i.e., requiring minimal information processing), a growing body of research is showing that the process of maintaining or regaining stability requires attentional resources (Abernethy, Hanna, & Plooy, 2002; Cherng, Liang, Hwang, & Chen, 2007; Huang, Mercer, & Thorpe, 2003; Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1993). Attentional resources have been defined as available information-processing resources, and are assumed to be limited (Kahneman, 1973; Wickens, 1989). As a result, competition for processing resources may occur during the performance of more than one attentionally demanding task and lead to task interference (Kahneman, 1973; Wickens, 1989). Research for studying attention and posture control has used dual task paradigms in which balance control during quiet standing or gait (the primary task) and a secondary task were performed together (Huang & Mercer, 2001; Woollacott & Shumway-Cook, 2002). The degree to which performance on either one or both tasks declined has been used to show the extent of attentional resource sharing. Experiments using dual task designs have led researchers to propose a hierarchy of postural tasks based on attentional processing requirements. The least resources are required for non-demanding postural tasks such as sitting or standing with feet shoulder width apart; attentional demands increase when standing in tandem Romberg position (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008), walking (Lajoie, Teasdale, Bard, & Fleury, 1993), during obstacle avoidance while walking (H. C. Chen et al., 1996), and during recovery from external perturbations (Brown, Shumway-Cook, & Woollacott, 1999;

Rankin, Woollacott, Shumway-Cook, & Brown, 2000). Attentional demands of walking were studied by Chen et al who showed that when subjects were asked to simultaneously perform a secondary visual scanning task while walking and avoiding an obstacle, the presence of the secondary task degraded the obstacle avoidance success rate (H. C. Chen et al., 1996).

Attentional Demands of Postural and Gait Control Are High in Children

Typically developing children demonstrate a marked reduction in the ability to perform a postural task and a cognitive task simultaneously compared to adults (Cherng, Su, Chen, & Kuan, 1999; Reilly, van Donkelaar, Saavedra, & Woollacott, 2008). This has been demonstrated as either a reduction in the performance of the cognitive task, specifically an increase in reaction time, and a concomitant decrement in the postural task (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008), or in a decrement of the postural task performance alone (Cherng, Su, Chen, & Kuan, 1999), depending on the difficulty of the tasks. It has also been shown that there are specific neuropsychological predictors of poor obstacle avoidance performance in dual task paradigms and these include variability in attention (Persad et al., 1995).

However, the ability to allocate attention increases with increasing age. TD children reach adult-like ability to allocate attention at age 7 (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008). Because sensory integrative function and reweighting are immature in children aged less than 7 years, postural control interference is seen in younger children more than older children and adults (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008).

Attentional Demands of Postural Control Vary with Balance Abilities

What is the relationship between attention and postural control in children with CP? No studies have yet been performed to test the attentional demands of postural control in children with CP during dynamic tasks such as walking. Studies have been performed on other patient populations and have reported that performance of a dual task had a deleterious effect on the ability to recover stability (Catena, van Donkelaar, & Chou, 2007; H. C. Chen et al., 1996). One mechanism contributing to this loss was reduced muscle activity during recovery of balance when performing the secondary task (Reed, 1982). In addition, increasing postural demands (recovery of stability following platform perturbations of increasing velocities) reduced the accuracy of performance on a secondary cognitive task (Brauer, Woollacott, & Shumway-Cook, 2001, 2002; Brown, Shumway-Cook, & Woollacott, 1999; Lindenberger, Marsiske, & Baltes, 2000). We have hypothesized that an inability to produce an appropriate postural response due to the competition for attentional resources between the demands of the postural system and the cognitive task may contribute to falls in children with CP with poor balance. A number of studies examining postural control under dual task conditions in balance impaired patient populations suggest support for this hypothesis. Patients with clinical balance impairments either stop (Lundin-Olsson, Nyberg, & Gustafson, 1997) or take a longer time to complete a gait task when performed with an additional secondary task (A.

Shumway-Cook, Brauer, & Woollacott, 2000). Further evidence that competition for attention may play a role in instability and falls in patients with balance impairment was reported in a study that found that as sensory conditions became more difficult, patients with balance impairment who had been able to maintain stability in a single task context, lost balance and had to be caught to prevent a fall, in a dual task context (A. Shumway-Cook & Woollacott, 2000).

The Effects of Types of Secondary Cognitive Task on Postural Control

Many types of secondary tasks have been used to study attentional mechanisms using the dual-task methodology. These include both sensory tasks involving the visual or auditory systems, the Stroop task (involving executive attention), verbal memory tasks, and math tasks, such as counting backwards by threes.

To test the interference of visual spatial versus nonvisual pathways on stance postural control Kerr and colleagues compared the performance of subjects on a verbal working memory and a spatial working memory task and showed that spatial working memory tasks interfered with postural control while verbal memory tasks did not (Kerr, Condon, & McDonald, 1985). More recently, Maylor and Wing compared interference between stance posture control and secondary tasks that involved different components of working memory, including visual spatial memory, and phonological systems (Maylor & Wing, 1996). They showed that within the tasks they used, visual spatial memory was most affected by the stance postural task. Though these studies are interesting, they may be weakened by not differentiating between structural attentional interference and capacity attentional interference.

According to a model by Kahneman (Kahneman, 1973), the total available processing capacity of any individual is limited. Thus, limited processing capacity within an individual, due to attentional deficits or minimal cognitive impairments, also may contribute to reduced performance in dual task situations. As soon as the processing capacity is exceeded during dual-task activities, performance on at least one of the tasks will drop. Kahneman also noted that two types of attentional interference are possible, structural interference (use of the same input or output system overloading the capacity of that system) and capacity interference (total central processing is exceeded by the 2 tasks). He notes that if you want to study capacity interference it is important to choose tasks that do not introduce structural interference. To exclude the possibility of structural interference, it is therefore best to use secondary tasks that do not interfere with the visual or somatosensory control systems for balance or locomotion. Thus in a recent study, Weerdesteyn et al used an auditory Stroop task (identifying a high or low tone pitch during conditions in which the tone is presented using the word "high" or "low" either in consonance with the pitch or in conflict with the pitch) as the secondary task when examining obstacle avoidance during gait under dual-task conditions (Weerdesteyn, Schillings, van Galen, & Duysens, 2003). Therefore, the auditory Stroop task will be used as a secondary cognitive task in this study.

Study Proposal

The prior summary of the research literature related to postural control during gait in TD children and children with CP indicates lack of information on mechanical changes associated with development of balance control in these children, especially the effects of dual task conditions. There is almost no previous research exploring changes in the attention requirements of gait postural control during development in TD children or children with CP. In addition, despite the fact that trips or slips during locomotion are a primary reason for balance loss, no one has characterized developmental changes in the ability to maintain and recover stability during perturbed locomotion (for example, obstacle clearance tasks) in dual task conditions.

The aim of the study is to address these research questions.

1. What developmental changes occur in the ability of TD children to performing a cognitive task (the auditory Stroop task) and a gait task simultaneously as opposed to performing the two tasks separately?

2. What are the developmental trends in the attentional requirement of gait postural control when the gait postural control task increases in difficulty like an obstacle crossing task?

3. Though previous research has shown that there is interference between static postural control and performance of a secondary task in children with CP, the effects of a dual task on gait postural control in these children have not been studied. This raises the question of what the influences of a cognitive task (the auditory Stroop task) on gait postural control in children with CP are.

To answer these questions, the experiments in this study were designed to examine typical development in children (younger vs. older TD children) of gait postural control using a dual task paradigm and to compare this development with that of children with CP. Particularly, three hypotheses were proposed to explore the mechanisms contributing to the development of gait postural control under dual task conditions: There would be 1) increased attentional requirements for postural control during gait in younger compared to older TD children, as well as deterioration in gait during the performance of a cognitive task, 2) increased attentional resources required when task difficulty was increased, and 3) increased attentional requirements for postural control during gait in children with CP compared to TD peers.

Hypothesis one: There would be increased attentional requirements for postural control during gait in younger compared to older TD children as well as deterioration in gait during the performance of a cognitive task

To test this hypothesis, gait and cognitive parameters measured from a dual task situation were compared with those measured from a single task situation. The hypothesis can be rejected if older TD children show greater interference between gait and cognitive performances than younger TD children. Alternatively, this hypothesis can be accepted if older TD children demonstrate less interference between gait and cognitive tasks in dual task contexts compared with younger children with typical development.

Hypothesis two: Additional attentional resources would be required when the postural task increased in difficulty.

To determine whether gait and cognitive performance under dual task conditions in younger and older TD children would be reduced when performing a more difficult postural task, performance was compared on level walking (an easier postural task) and obstacle crossing (a more challenging postural control task)

Hypothesis three: There would be increased attentional requirements for postural control during gait in children with CP compared to TD peers.

To test this hypothesis, dual task performance of postural and cognitive tasks of younger and older TD children and children with CP were compared with single task performance. This hypothesis can be rejected if dual task performance in children with CP is the same as their age matched peers who are typically developing. Alternatively, this hypothesis can be accepted if children with CP demonstrate decreased performance in dual task compared to single task contexts when compared to age-matched TD children.

Bridge

The first two research queries were to investigate the influences of a cognitive task (the auditory Stroop task) on the development of gait postural control and examine the developmental trends in the attentional requirement of gait postural control when a postural task becomes difficult. Regarding these queries, a dual task paradigm was used in which level walking or obstacle crossing and the auditory Stroop task were performed simultaneously. The general method for the experiments is described in Chapter II. The changes in attentional demands associated with the maintenance of gait postural control under normal and obstacle crossing conditions in TD children are discussed in Chapter III.

Chapter IV gives evidence for the effects of performing a secondary cognitive task on postural control during gait among younger and older TD children and children with CP. Chapter III and IV includes unpublished co-authored materials. Co-authors would be P. van Donkelaar, L.S. Chou, and M. H. Woollacott for both Chapter III and IV. Finally, the last chapter (Chapter V) summarizes the conclusions drawn from the major findings of each experiment, discusses the limitations of the study and offers suggestions for how this research might be applied to the assessment and treatment of children with CP.

CHAPTER II

GENERAL METHODOLOGY

Participants

To determine the developmental changes that occur in the ability of typically developing (TD) children to perform a cognitive task (the auditory Stroop task) and a gait task simultaneously, 40 children with typical development ranging from 5 to 16 years of age without known musculoskeletal, neurological and cognitive deficits reported by their parents or guardians were recruited for this study. Two subgroups of participants who were matched in gender were separated based on the children's chronological age. These included 20 younger children with typical development (YTD) aged 5 to 6 years and 20 older children with typical development (OTD) aged 7 to 16 years.

To determine if there are any differences in the ability of children with cerebral palsy (CP) and TD children to performing a cognitive task (the auditory Stroop task) and a gait task simultaneously, 20 YTD children (5-6 yrs) and 20 OTD children (7-16 yrs) were used as comparison groups for the children with CP. Ten children with spastic CP aged 7-18 years were recruited as subjects for this study. They were required to meet the following inclusion criteria for the study: 1) diagnosed with spastic cerebral palsy, 2) walking without restrictions or assistive devices (Gross Motor Functional Classification System (GMFCS) level 1-2), and 3) no speech or auditory disability. The children with

CP were also given a clinical examination by a pediatrician to confirm the severity and diagnosis of type of cerebral palsy.

Prior to experimental testing, participants and their parents or guardians were provided written and verbal instructions of testing procedures. The informed consent approved by the Human Subjects Compliance Committee of the University of Oregon was obtained from parents or guardians prior to testing. Parents or guardians completed a Healthcare Questionnaire to identify possible neuromuscular impairments that could affect their child's gait performance. They also completed the attention deficit hyperactivity disorder (ADHD) checklist and the Children's Behavior Checklist (CBCL) to identify whether their child might have the potential to have cognitive deficits.

In addition, all participants were examined using the Gross Motor Function Measure (GMFM-88) (Russell, Rosenbaum, Avery, & Lane, 2002) for dimension D (standing) and dimension E (walking, running & jumping) and were also tested for balance ability, and cognitive function using the Pediatric Balance Scale (PBS) (Franjoine, Gunther, & Taylor, 2003), and a child version of the Attentional Network Test (ANT) (Rueda et al., 2004), respectively.

Experimental Apparatus

All data were collected in the Motor Control Laboratory of the University of Oregon. The eight-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) with sample rate of 60 Hz and a fourth-order Butterworth filter with cutoff frequency of 8 Hz was used to collected three dimensional marker trajectories in space. A set of 29 reflective markers was placed bilaterally on bony landmarks of the body similar to previous studies published by Chou and colleagues (Hahn & Chou, 2004; Parker, Osternig, van Donkelaar, & Chou, 2007; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

For the obstacle crossing task, the obstacle was a wooden dowel (0.9 cm diameter, 91 cm long) placed on top of two adjustable upright stands. The crossbar would easily come loose and fall to the ground if struck by the child's foot. The height of the crossbar was adjusted to 10% of each child's body height. A marker was placed at each end of the crossbar to track its global position.

An auditory Stroop task was used as a secondary cognitive task. Stimuli were relayed to the participant through two speakers facing the walkway. The stimuli which were presented to the participant included the word "high or "low" spoken with a high or low pitch. Congruency between pitch and the word was randomized. The participant was asked to indicate the pitch of the voice as quickly and accurately as possible by saying "high" or "low" while ignoring the actual word that was presented. One infrared-beam located 40 cm before the obstacle and 45 cm above the ground was used for triggering the initiation of the Stroop task program to ensure that participants would hear the stimulus during swing phase of gait (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

Experimental Protocol

The experimental testing started and ended with a block of 4 trials of the seated Stroop task. Each trial was composed of 4 stimuli of the spoken word "high" or "low" in "high" or "low" pitch. Congruency between the word and pitch were randomized. The participants were given several practice trials before data collection. Verbal reaction time and accuracy of the responses were collected during sitting as the baseline (or control) to determine the extent to which additional balance constraints require attentional resources and thus reduce performance on the secondary tasks. After marker placement, participants wore a safety harness attached to a trolley system secured to a concrete ceiling to prevent injury from an accidental fall and were allowed to walk along an 8-meter walkway for several trials to make them familiar with the marker set and the harness, resulting in comfortable walking. Then, participants were asked to walk along the walkway under different walking conditions and sequences depending on their group. In children with cerebral palsy, they were asked to perform a block of the level walking task beginning with 12 trials of level walking followed by 12 trials of level walking with a secondary task. Ten YTD children and 10 OTD children who were comparison groups to the children with CP were asked to perform the same block of level walking task as the children with CP. After that, they were asked to perform a block of the obstacle crossing task, beginning with 12 trials of obstacle crossing followed by 12 trials of obstacle crossing with a secondary task.

To counter balance the effects of fatigue and learning when comparing gait and cognitive performances between lower and higher developmental age children, the remaining 10 YTD children and 10 OTD children were asked to perform a block of the obstacle crossing task followed by a block of the seated Stroop task, a block of the level walking task and another block of the seated Stroop task (see Figure 2.1). The auditory Stroop task for walking tasks was composed of 1 stimulus per trial with randomized word and pitch. Participants were instructed by the proctor to perform the walking task at their preferred speed and that in the dual-task condition, they had to respond as quickly and accurately as possible. Participants were allowed to take a break if they felt tired or fatigued.

Data Processing and Analysis

The regression equations from Jensen's report (Jensen, 1986) were applied to define the segment mass of 15-body segments including head, trunk, two upper arms, two forearms, two hands, pelvis, two thighs, two legs, and two feet. These segmental masses were used to compute the whole-body center of mass (COM) (Winter, 2009). The average medial COM-ankle-joint-center inclination angle (Med COM-AJC) throughout the single stance phase of gait was computed. This angle was formed by the intersection between a line from the COM location to ankle joint center, and a vertical line through the ankle joint center in the coronal plane (Silsupadol et al., 2009). In addition, the COM range of motion in the sagittal plane (AP ROM) and in the coronal plane (ML ROM) as well as the peak linear velocities of the COM in the sagittal and coronal planes (AP V and ML V) during the crossing stride were used to quantify the child's dynamic stability when walking and stepping over the obstacle.

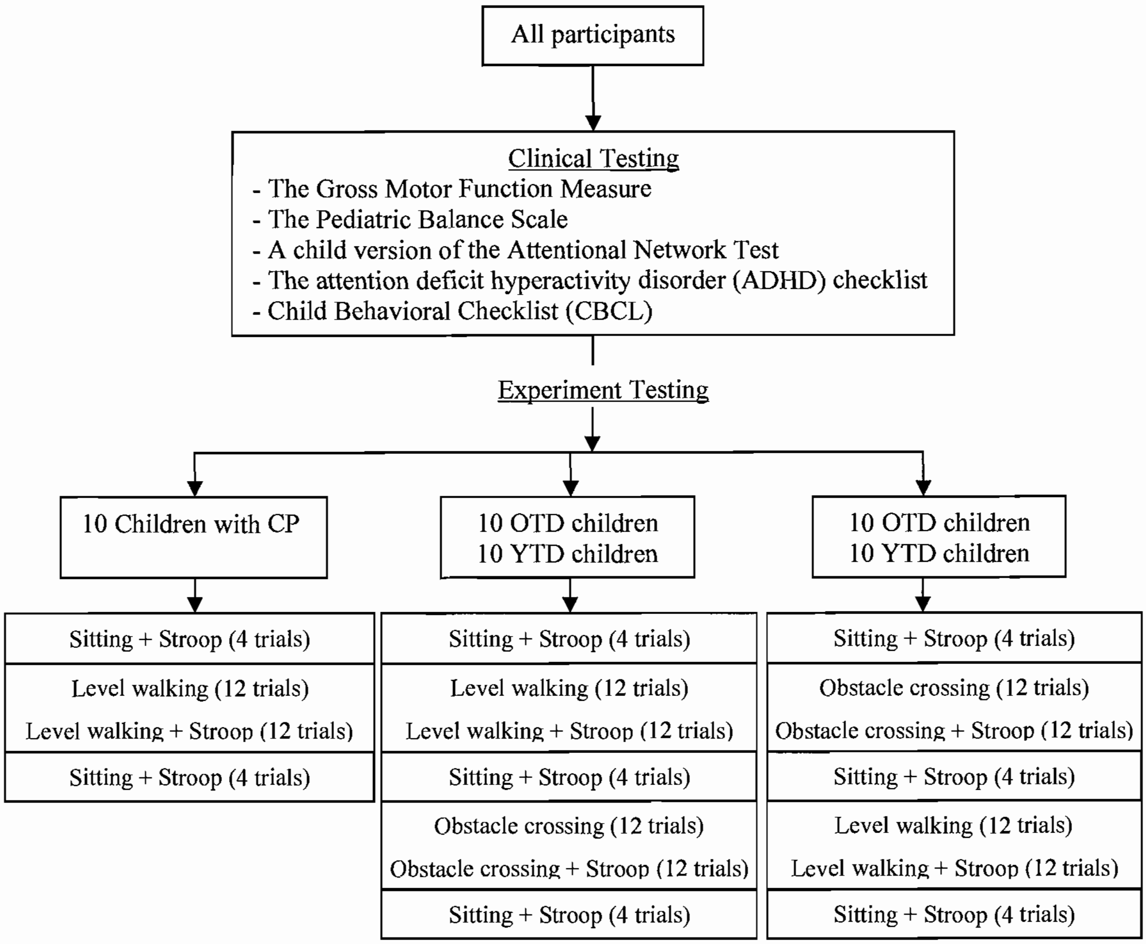


Figure 2.1. Experiment Protocol (CP = cerebral palsy, OTD = older children with typical development, YTD = younger children with typical development, + Stroop = plus the auditory Stroop task)

Temporal-spatial gait parameters including gait velocity, stride length, stride time, and average step width were calculated during the crossing stride. Stride length and stride time were determined from the position and the relevant time changes of the heel marker. Additional obstacle crossing parameters including trailing toe obstacle clearance (TTOC), trailing toe distance (TTD), leading heel distance (LHD), and leading toe obstacle clearance (LTOC) during the crossing stride were also computed for obstacle crossing trials. TTOC and LTOC were the vertical distance from toe marker of the trailing and leading limbs to the obstacle bar. TTD and LHD were the horizontal distance from the toe marker of the trailing limb and the heel marker of the leading limb to the obstacle, respectively. All temporal-spatial parameters were normalized by the method of Hof (1996) (Table 2.1) (Hof, 1996; Stansfield et al., 2003). Data from successful (non-tripping) trials for each testing condition were used in formulating the results and performing statistical analysis.

Table 2.1. Normalized formulas for temporal-spatial variables (Hof, 1996).

Dependent Variables	Normalized formulas
Center of mass (COM)	
- Anterior-Posterior range of motion (AP ROM)	AP ROM / height
- Medial-Lateral range of motion (ML ROM)	ML ROM / ASIS width
- Peak Anterior-Posterior linear velocity (AP V)	AP V / $(g^{*} \text{ height})^{1/2}$
- Peak Medial-Lateral linear velocity (ML V)	ML V / $(g^{*} \text{ ASIS width})^{1/2}$
Temporal-spatial gait variables	
- Gait velocity (GV)	GV / $(g^{*} \text{ height})^{1/2}$
- Stride time (ST)	ST / $(\text{height} / g)^{1/2}$
- Stride length (SL)	SL / height
- Step width (SW)	SW / ASIS width
Obstacle crossing variables	
- Trailing toe distance (TTD)	TTD / height
- Trailing toe obstacle clearance (TTOC)	TTOC / height
- Leading toe obstacle clearance (LTOC)	LTOC / height
- Leading heel distance (LHD)	LHD / height

ASIS width = distance between right and left anterior superior iliac spine (ASIS), g = gravitational acceleration (9.81 m/s^2).

For the auditory Stroop task, verbal reaction time (VRT) of the corrected responses and percentage of the corrected responses were calculated. VRT was the duration difference between the onset of stimulus and the onset of verbal response. Accuracy of the responses was reported in the percentage of the total responses.

The amount of dual task interference between gait and cognitive performance was determined by dual-task costs. Dual task costs represented the percentage of performance reductions of each individual's single task performance when performing the two tasks concurrently. Positive values indicate performance decrements in the dual task context, whereas negative values indicate performance improvements from the single to dual task context (Schaefer, Krampe, Lindenberger, & Baltes, 2008). Normalized gait measures, VRT and accuracy were used to calculate dual-task costs in formula (1) for gait velocity, stride length, AP ROM, AP V, TTD, TTOC, LTOC, LHD, and accuracy, and in formula (2) for stride time, step width, ML ROM, ML V, Med COM-AJC, and VRT.

$$((\text{Single} - \text{Dual}) / \text{Single}) \times 100 \qquad \text{-----------------} \ (1)$$

$$((\text{Dual} - \text{Single}) / \text{Single}) \times 100 \qquad \text{-----------------} \ (2)$$

Statistical analyses were performed with SPSS for Windows v.16. One-way ANOVA analysis was used to examine the children's balance ability, motor functional skill, and attention functional ability. A mixed model analysis of variance was used to examine the main effects and interaction effects of independent factors based upon the conditions. Gait parameters including gait velocity, stride length, stride time, step width, TTOC, TTD, LHD, LTOC, AP ROM, ML ROM, AP V and ML V, and the Stroop parameters including percentage of accuracy and VRT were used as dependent variables.

Pairwise comparisons were carried out using a Bonferroni correction to identify the direction of gait and cognitive performance changes. The dual-task costs were examined by using planned comparisons ANOVA. Significance level was set at $p<0.05$.

Bridge

The next chapter summarizes research examining the developmental changes that occur in the ability of TD children to perform a cognitive task (the auditory Stroop task) and a gait task simultaneously. This study suggests that TD children require attention to maintain gait postural control. The dual task interference between gait and cognitive performance was greater in younger children than in older children. In addition, the amount of interference between gait and cognitive task performances did not increase when the difficulty of the gait postural task increased.

CHAPTER III

DEVELOPMENT OF POSTURAL CONTROL DURING GAIT IN TYPICALLY DEVELOPING CHILDREN: THE EFFECTS OF DUAL TASK CONDITIONS

Drs. P. Dassonville, P. van Donkelaar, L.S. Chou, and M. H. Woollacott helped with the creation of the conceptual design for this experiment. The experimental procedure, including data collection and analysis, described in this chapter was carried out by me. I was the primary contributor to the writing of the research article.

Gait control has traditionally been thought as an autonomic function like reflexive control, requiring minimal higher cognitive processing. However, recent research has provided evidence indicating that gait control requires attentional resources (Cherng, Liang, Hwang, & Chen, 2007; Ebersbach, Dimitrijevic, & Poewe, 1995; Huang, Mercer, & Thorpe, 2003; Lajoie, Teasdale, Bard, & Fleury, 1993; Lindenberger, Marsiske, & Baltes, 2000). Attentional resources have been defined as available information-processing resources, and are assumed to be limited (Kahneman, 1973; Wickens, 1989). Competition for limited attentional resources may occur when performing more than one attentionally demanding task at one time. In the case that the available limited resources are less than the demands of both tasks, deterioration in performance of one or both tasks will be expected (Kahneman, 1973; Wickens, 1989).

Research studying attentional resources required for postural control has typically used a dual task paradigm, in which young adult participants are asked to perform a primary postural or gait task and a secondary cognitive task simultaneously (Huang & Mercer, 2001). In addition, a small number of studies in gait control has explored the ability of children to perform both gait and a secondary cognitive task simultaneously (Cherng, Liang, Hwang, & Chen, 2007; Huang, Mercer, & Thorpe, 2003). These studies have demonstrated that walking while performing a concurrent cognitive task caused a reduction in gait velocity, cadence and stride length, and an increase in double limb support time and base of support (Cherng, Liang, Hwang, & Chen, 2007; Huang, Mercer, & Thorpe, 2003). However, these previous studies have not shown developmental trends for gait control in children, as only one group of children was included in the studies. In addition, these studies have not explored mechanisms underlying gait postural control in dual task situations in children.

Previous research has demonstrated that dual task interference with gait performance varies depending on the type of secondary cognitive task (Ebersbach, Dimitrijevic, & Poewe, 1995; Huang, Mercer, & Thorpe, 2003; Kerr, Condon, & McDonald, 1985; Maylor & Wing, 1996). In order to study if interference due to information processing capacity limitations are the primary factor contributing to performance deficits in dual task contexts, it is important to choose tasks that do not introduce structural interference (for example, using tasks that both require visual pathways) (Kahneman, 1973). To exclude the possibility of structural interference, it is therefore best to use secondary cognitive tasks that do not interfere with the visual or somatosensory control systems contributing to the control of balance or locomotion. Thus, recent studies used the auditory Stroop task as a secondary cognitive task when examining obstacle avoidance during gait under dual task conditions. In this task the participant identified a high or low tone pitch during conditions in which the tone was presented using the word "high" or "low" either in consonance with the pitch or in conflict with the pitch (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008; Weerdesteyn, Schillings, van Galen, & Duysens, 2003). In order to exclude the possibility of structural interference between the two tasks in the present study, the auditory Stroop task was used as a secondary cognitive task as well.

It has previously been demonstrated that different types of postural tasks require varying amounts of attentional resources, with more difficult balance tasks requiring increased attention resources (Ebersbach, Dimitrijevic, & Poewe, 1995; Lajoie, Teasdale, Bard, & Fleury, 1993; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). It is reasonable to expect that maintaining dynamic balance of the whole body during obstacle crossing may be a more challenging task than during unobstructed level walking, as the longer swing time required for the swing limb implies a longer duration of single stance for the supporting limb when stepping over an obstacle. Greater and faster motion of body segments while negotiating an obstacle would result in greater and faster movement of the center of mass (COM) and perturb balance maintenance (Chou & Draganich, 1997; Patla & Rietdyk, 1993). Recent research in healthy young adults has shown that obstacle crossing required more attentional resources than sitting or level walking (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

Research on children who are typically developing has examined both single and dual task requirements of anticipatory postural control during locomotion. Studies have demonstrated that children aged 7-9 years old have reached adult-like proactive control in their strategies to avoid obstacles (McFadyen, Malouin, & Dumas, 2001). Moreover, other studies have shown that the ability to allocate attention in quiet stance postural control children has reached adult-like levels by age 7 (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008). It has also been shown that sensory integrative function and reweighting of sensory inputs under different environmental conditions were also immature in children aged less than 7 years. Thus immaturity of the postural control systems (possibly associated with increased attentional requirements) may contribute to the secondary task interference with postural control seen in younger children (4-6 yrs), as compared to older children and adults (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008).

Previous research has not explored the influences of a concurrent cognitive task (the auditory Stroop task) on the development of gait postural control in children with typical development as well as the effects of a gait task difficulty on a dual task gait postural control in these children. Therefore, the purpose of this study was to investigate the development of postural control during gait under dual task conditions, comparing younger children with typical development (YTD) aged 5-6 years, older children with typical development (OTD) aged 7-16 years and healthy young adults (HYA) aged 19-26 years. We have hypothesized that, when compared with HYA, YTD and OTD children would show greater interference between gait and cognitive task performance while concurrently performing walking and a secondary cognitive task. Dual task interference between gait and cognitive task performance in YTD children would be greater than in OTD children. Finally, the study aimed to further investigate the attentional requirements of a more challenging gait task, obstacle crossing. It has been hypothesized that increasing the difficulty of the gait task would produce corresponding increases in the amount of interference between the gait task and a concurrent secondary cognitive task, especially in YTD children.

Methods

Participants

Forty children with typical development participated in the study. They were subdivided into 2 groups according to chronological age: 20 younger children with typical development (YTD) aged 5-6 years (9 females/11 males; age = 6.22 ± 0.63 years) and 20 older children with typical development (OTD) aged 7-16 years (9 females/11 males; age = 10.92 ± 2.95 years). The children had no known neuromuscular diseases or attentional deficits according to their parents' and teachers' reports. Prior to children entering the study, informed consent approved by the Human Subjects Compliance Committee of the University of Oregon, was obtained from the child and their parents or guardians.

Children were assessed for motor function and balance ability by using the Gross Motor Function Measure (GMFM-88) (Russell, Rosenbaum, Avery, & Lane, 2002) for dimension D (standing) and dimension E (walking, running & jumping) and the Pediatric

Balance Scale (PBS) (Franjoine, Gunther, & Taylor, 2003). In addition, a children's version of the Attentional Network Test (ANT) (Rueda et al., 2004) was used to test for the level of children's attentional abilities.

Finally, children's gait and cognitive performance in the present study was compared with 12 healthy young adults (5 females/7 males; age = 22.83 ± 2.66 years) who had been studied by Siu et al (2008).

Equipment

An eight-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) with a sample rate of 60 Hz and a fourth-order Butterworth filter with cutoff frequency of 8 Hz was used to capture three dimensional marker trajectories in space. A set of 29 reflective markers was placed bilaterally on bony landmarks of the children's body similar to previous studies (Hahn & Chou, 2004; Parker, Osternig, van Donkelaar, & Chou, 2007; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). Fifteen body segments, including head, trunk, 2 upper arms, 2 forearms, 2 hands, pelvis, 2 tights, 2 legs, and 2 feet, were used in this study. The regression equations from Jensen's report (Jensen, 1986) were applied to define the segments' mass and the center of mass (COM).

The walkway was 8-meter long. An obstacle was placed in the middle of the walkway for the obstacle crossing task. The obstacle was a wooden dowel (0.9 cm diameter, 91 cm long) placed on top of two adjustable upright stands. The height of the crossbar was adjusted to 10% of each child's body height. One infrared-beam used for triggering the initiation of the auditory Stroop task program was set to ensure that children would hear the stimulus during single limb support or while crossing the obstacle (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

Procedures

After marker placement, children in each group were asked to perform the following tasks: Three blocks of 4 trials of the auditory Stroop task in sitting at the beginning and at the end of the testing, and also between a block of level walking and a block of obstacle crossing tasks. Each trial of the seated Stroop task was composed of 4 stimuli of the spoken word "high" or "low" in a "high" or "low" pitch. In a block of level walking and obstacle crossing tasks, children were asked to perform 12 trials of level walking or obstacle crossing tasks in isolation, and another 12 trials of these tasks with the auditory Stroop task. There was a single auditory Stroop stimulus for each trial of level walking and stepping over the obstacle tasks. Congruency between the word and pitch of the auditory Stroop task were randomized. Each child was instructed to respond to the pitch of the voice as quickly and accurately as possible.

To counterbalance for possible fatigue and learning effects, half of the children in each group were asked to first perform a block of level walking trials and then perform a block of obstacle crossing trials. The other half of the children were asked to perform the obstacle crossing task before the level walking task. Children were instructed to walk at their preferred speed and they wore a safety harness attached to an overhead trolley system to prevent injury from an accidental fall while walking. Several practice trials for each task were given to the children before collecting data. Children were allowed to take a rest if they became fatigued.

Data Processing and Analysis

The regression equations from a study by Jensen (Jensen, 1986) were applied to define the segment mass of 15-body segments including head, trunk, two upper arms, two forearms, two hands, pelvis, two thighs, two legs, and two feet. These segmental masses were used to compute the whole-body center of mass (COM) (Winter, 2009). The COM range of motion in the sagittal plane (AP ROM) and in the coronal plane (ML ROM), as well as the peak linear velocities of the COM in the sagittal and coronal planes (AP V and ML V) during the crossing stride were used to quantify the child's dynamic stability when walking and stepping over the obstacle.

Temporal-spatial gait parameters, including gait velocity, stride length, stride time, and average step width, were calculated during the crossing stride. Stride length and stride time were determined from the position and the relevant time changes of the heel marker. Additional obstacle crossing parameters, including trailing toe obstacle clearance (TTOC), trailing toe distance (TTD), leading heel distance (LHD), and leading toe obstacle clearance (LTOC) during the crossing stride, were also computed for obstacle crossing trials. TTOC and LTOC were the vertical distance from the toe marker of the trailing and leading limbs to the obstacle bar. TTD and LHD were the horizontal distance from the toe marker of the trailing limb and the heel marker of the leading limb to the obstacle, respectively. All gait measures were normalized by using Hof's method (Hof,

1996) to eliminate the effect of body size (Table 3.1). Data from successful (non-tripping) trials for each testing condition were used in formulating the results and performing statistical analysis.

Table 3.1. Normalized formulas for gait measures.

Dependent Variables	Normalized formulas
Center of mass (COM)	
- Anterior-Posterior range of motion (AP ROM)	AP ROM / height
- Medial-Lateral range of motion (ML ROM)	ML ROM / ASIS width
- Peak Anterior-Posterior linear velocity (AP V)	AP V / $(g*height)^{1/2}$
- Peak Medial-Lateral linear velocity (ML V)	ML V / $(g*\ ASIS\ width)^{1/2}$
Temporal-spatial gait variables	
- Gait velocity (GV)	GV / $(g*\ height)^{1/2}$
- Stride time (ST)	ST / $(height\ /\ g)^{1/2}$
- Stride length (SL)	SL / height
- Step width (SW)	SW / ASIS width
Obstacle crossing variables	
- Trailing toe distance (TTD)	TTD / height
- Trailing toe obstacle clearance (TTOC)	TTOC / height
- Leading toe obstacle clearance (LTOC)	LTOC / height
- Leading heel distance (LHD)	LHD / height

ASIS width = distance between right and left anterior superior iliac spine (ASIS), g = gravitational acceleration (9.81 m/s^2).

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

Gait and cognitive performance changes from single to dual task conditions were calculated in proportional dual-task costs. Dual task costs represent the percentage change in dual-task performance as compared to the individual's single task performance. Positive values indicate performance decrements whereas negatives values indicate performance improvements from single to dual task (Schaefer, Krampe, Lindenberger, & Baltes, 2008). Normalized gait measures, VRT, and accuracy were used to calculate dual-task costs in formula (1) for gait velocity, stride length, AP ROM, AP V, TTD, TTOC, LTOC, LHD, and accuracy, and in formula (2) for stride time, step width, ML ROM, ML V, and VRT.

$$((\text{Single} - \text{Dual}) / \text{Single}) \times 100 \quad \text{-----------------} \; (1)$$

$$((\text{Dual} - \text{Single}) / \text{Single}) \times 100 \quad \text{-----------------} \; (2)$$

Statistical analyses were performed with SPSS for Windows 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 children were determined by using independent t-tests. The main effects and the interaction effects of the independent factors on temporal-spatial gait measures, COM range of motion and peak linear velocity were determined by a three-way mixed-model factorial ANOVA with weighted mean; group (YTD, OTD and HYA) × task (level walking and obstacle crossing) × condition (single and dual tasks). A two-way mixed-model factorial ANOVA with weighted mean was applied to examine the main effects and the interaction effects of independent factors on VRT and accuracy; group (YTD, OTD and HYA) × 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 a Bonferroni correction to identify the direction of gait and cognitive performance changes. The dual-task costs were examined by using planned comparisons ANOVA. Pearson correlation analysis was used to test the correlation between ANT subsystems scores and the dual task effects on gait parameters.

Results

Baseline Characteristics

OTD children showed significantly higher performance scores for the GMFM for dimension E (walking, running and jumping) compared to YTD children ($t(38) = 2.430$, $p = 0.020$). 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 children. For the attentional network test, OTD showed significantly better performance scores than YTD children 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 ($p > 0.05$). The children's motor functional ability, balance ability, and cognitive functional ability are showed in Table 3.2.

Table 3.2. Means (SE) of gross motor functional ability, balance ability, and cognitive functional ability in younger children with typical development (YTD) and older children with typical development (OTD).

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

PBS = Pediatric Balance Scale, GMFM = Gross Motor Functional Measure, D = dimension D (standing), E = dimension E (walking, running and jumping), ANT = Attentional Network Test, *significant difference at $p < 0.05$.

Gait Performance

There were significant group main effects for step width ($F(2, 49) = 4.80$, $p = 0.01$, $\eta^2 = 0.16$). Pairwise comparison showed that YTD used a wider step width ($p = 0.01$) than HYA. A significant condition main effect was also found for step width ($F(1, 49) = 10.51$, $p < 0.01$, $\eta^2 = 0.18$). Pairwise comparisons demonstrated that participants in the present study demonstrated a wider step width ($p < 0.001$), when they performed gait tasks with a concurrent auditory Stroop task (Figure 3.1).

Significant group × 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 children used a slower gait velocity with a longer stride time and a shorter stride length ($p < 0.001$) when they simultaneously performed gait tasks and an auditory Stroop task. Decreased stride length was also found in OTD children when they performed in the dual task condition (Figure 3.1).

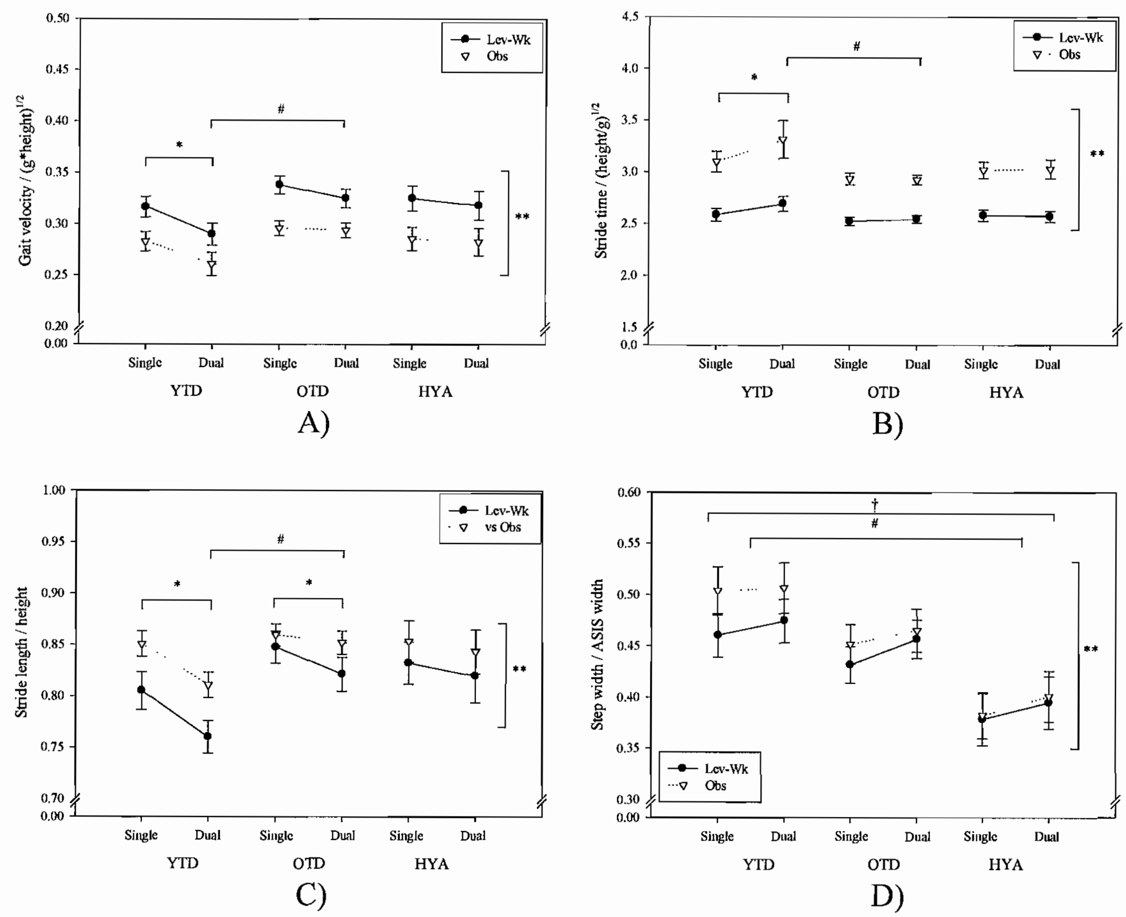


Figure 3.1. Normalized gait velocity (A), stride time (B), stride length (C), and step width (D) for level walking and obstacle crossing tasks under single and dual task conditions in younger and older children with typical development (YTD and OTD) and in healthy young adults (HYA).*Significant difference between single and dual task conditions 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.

Significant task main effects were found for gait velocity ($F(1, 49) = 60.69$, $p < 0.001$, $\eta^2 = 0.55$), stride time ($F(1, 49) = 59.53$, $p =< 0.001$, $\eta^2 = 0.55$), stride length $F(1, 49) = 23.98$, $p < 0.001$, $\eta^2 = 0.33$), and step width ($F(1, 49) = 9.12$, $p < 0.01$, $\eta^2 = 0.16$). Pairwise comparisons indicated that participants in the present study reduced gait velocity with longer stride time and stride length, and a wider step width in the obstacle crossing task ($p < 0.001$) as compared to the level walking task (Figure 3.1).

Gait Stability

There were significant group main effects for ML ROM ($F(2, 49) = 34.16$, $p < 0.001$, $\eta^2 = 0.58$), and ML V ($F(2, 49) = 11.37$, $p < 0.001$, $\eta^2 = 0.32$). Pairwise comparison showed that YTD showed greater ML ROM ($p < 0.001$) than HYA. In addition, YTD showed greater ML ROM ($p < 0.001$) and ML V ($p < 0.001$) than OTD.

Significant group × 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 children reduced AP ROM and AP V ($p < 0.001$) when they concurrently performed gait tasks and an auditory Stroop task. Decreased AP ROM ($p = 0.02$) was also found in OTD children when they performed in the dual task context (Figure 3.2). In contrast to children, HYA did not show any changes in COM displacement or linear velocity in the sagittal or coronal planes.

A significant task × 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 the obstacle crossing task (Figure 3.2).

Significant task main effects were found for AP ROM ($F(1, 49) = 102.36$, $p < 0.001$, $\eta^2 = 0.68$), ML ROM ($F(1, 49) = 28.27$, $p < 0001$, $\eta^2 = 0.37$) and ML V ($F(1, 49) = 39.47$, $p < 0.001$, $\eta^2 = 0.45$). Across all groups and conditions, ML ROM, and ML V were increased in the obstacle crossing task ($p < 0.001$) as compared to the level walking task (Figure 3.2).

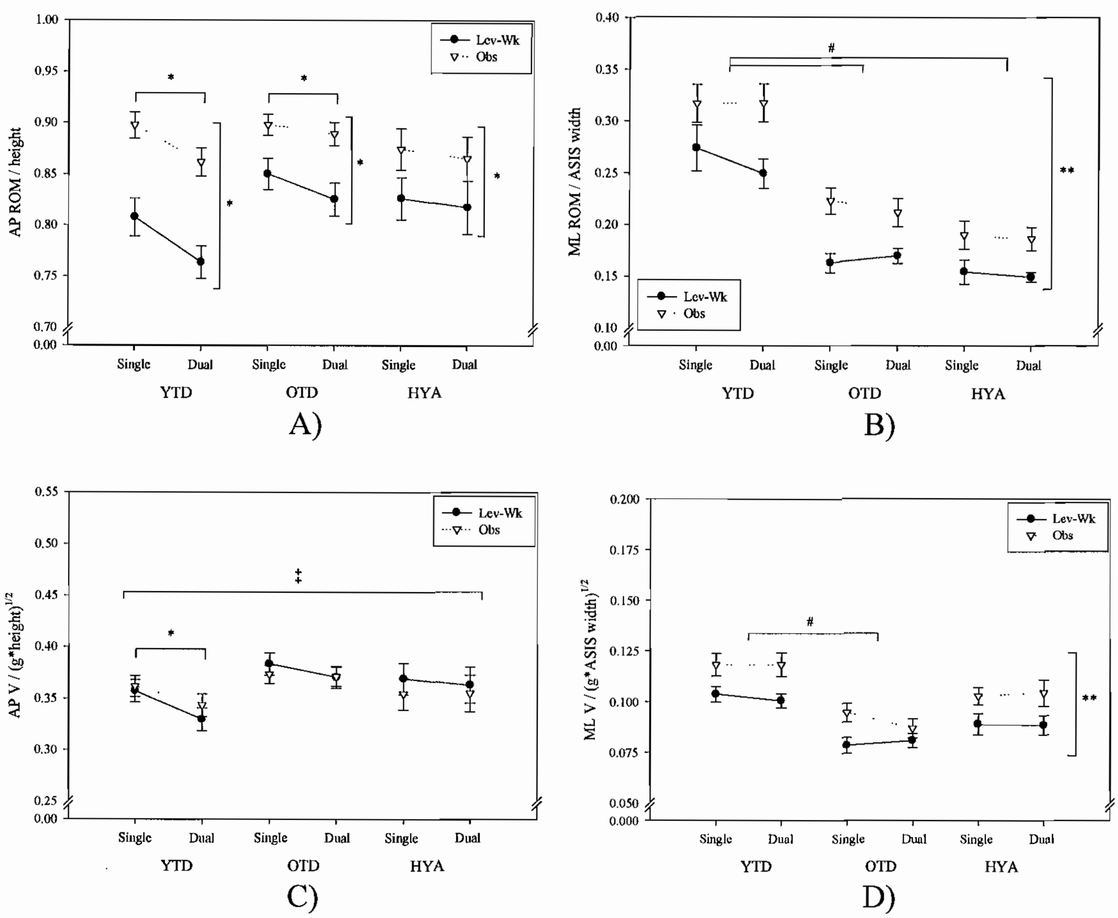


Figure 3.2. Normalized center of mass (COM) range of motion in (A) anterior-posterior plane (AP ROM) and in (B) medial-lateral plane (ML ROM), and normalized peak linear velocity of center of mass in (C) anterior-posterior plane (AP V), and in (D) medial-lateral plane (ML V) for level walking and obstacle 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.

A significant group × task interaction for AP ROM ($F(2, 49) = 4.39$, $p < 0.02$, $\eta^2 = 0.15$) was found. YTD children, OTD children and HYA increased AP ROM to negotiate the obstacle ($p < 0.01$). Pairwise comparisons also showed that there was no significant different in AP ROM between groups in the level walking task and the obstacle crossing task ($p > 0.05$) (Figure 3.2).

Obstacle Clearance Performance

In the obstacle crossing task, significant group main effects were found for trailing toe distance ($F(2, 49) = 4.96$, $p = 0.01$, $\eta^2 = 0.17$), LTOC ($F(2, 49) = 3.94$, $p = 0.03$, $\eta^2 = 0.14$), and LHD ($F(2, 49) = 3.75$, $p = 0.03$, $\eta^2 = 0.13$). Pairwise comparisons showed that YTD children performed with greater trailing toe distance and leading toe obstacle clearance and less leading heel distance than HYA ($p < 0.05$). In addition, YTD children demonstrated greater trailing toe distance than OTD children ($p < 0.05$). There was a significant condition main effect for leading heel distance ($F(1, 49) = 4.06$, $p < 0.05$, $\eta^2 = 0.08$). Pairwise comparisons indicated that dual tasking induced a reduction in leading heel distance ($p < 0.05$) (Figure 3.3).

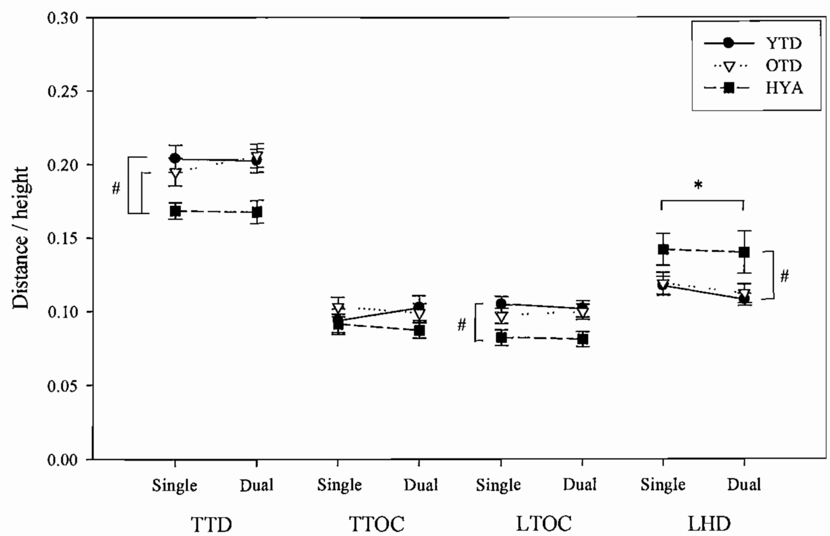
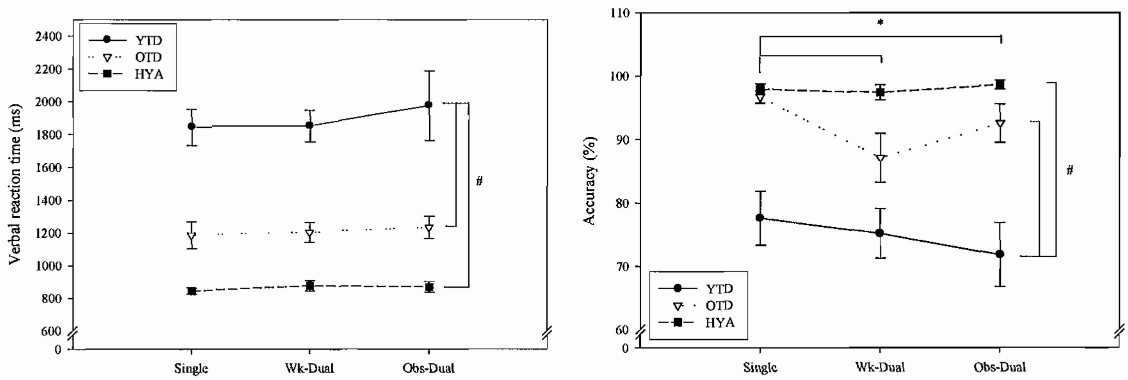


Figure 3.3. Normalized obstacle crossing measures in single and dual task situations in younger and older children with typical development (YTD and OTD) and in healthy young adults (HYA).TTD = trailing toe distance, TTOC = trailing toe obstacle clearance, LTOC = leading toe obstacle clearance, LHD = leading heel distance. *Significant difference between single and dual task conditions. #Significant difference between groups.

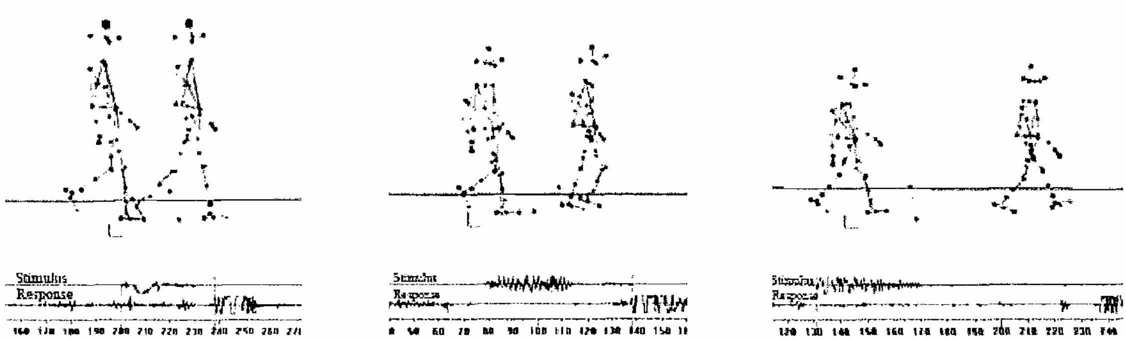
Auditory Stroop Task Performance

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 children performed with slower VRT (Figure 3.4a and 3.5) and less accuracy than older children and HYA ($p < 0.001$) (Figure 3.4b). Significant condition effects (F (2, 98) = 3.98, $p = 0.02$, $\eta^2 = 0.08$) were also found for accuracy. Pairwise comparisons indicated that accuracy was higher in the single task condition (sitting) than in dual task conditions (either level walking or obstacle crossing task) ($p < 0.05$). There was no significant difference in accuracy between two dual task conditions (level walking and obstacle crossing tasks) ($p > 0.05$) (Figure 3.4).



A) B)

Figure 3.4. Verbal reaction time (ms) (A) and accuracy (%) (B) for younger and older children with typical development (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.



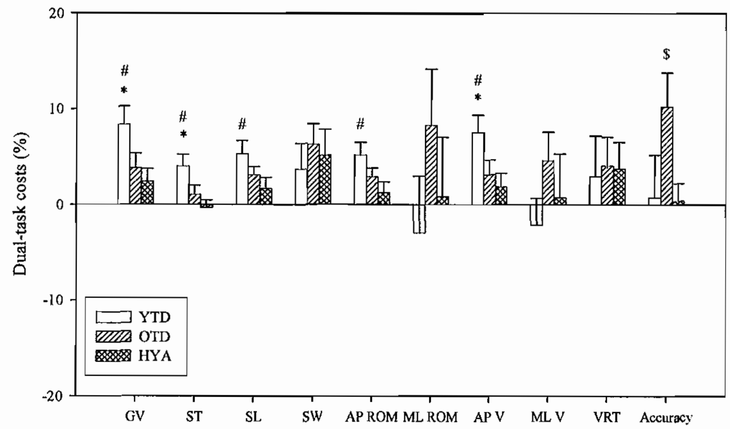
A) B) C)

Figure 3.5. 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) demonstrate the differences in the information processing among groups.

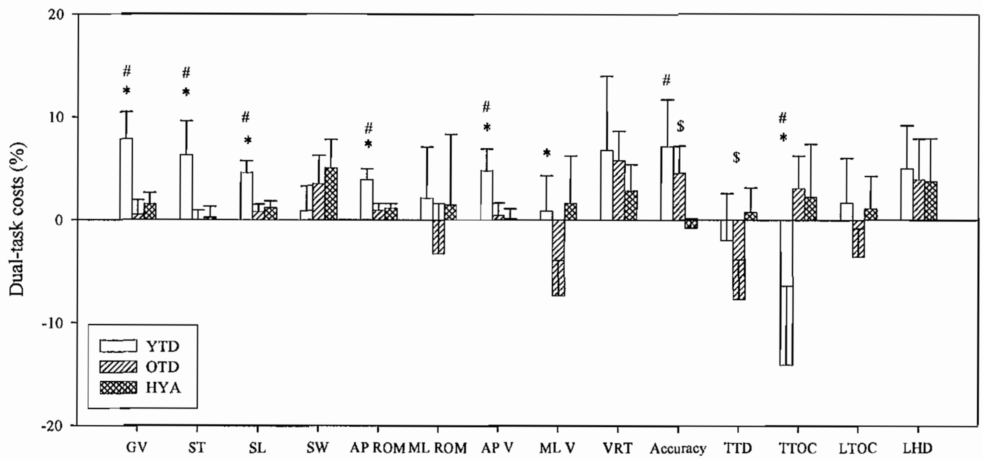
Dual-Task Costs

For gait stability, planned comparisons showed that, across all groups, dual-task costs for AP V were less in the obstacle crossing task than in the level walking task ($p = 0.03$). YTD children showed greater dual-task costs than HYA and OTD children for AP V ($p < 0.05$) in the level walking and the obstacle crossing tasks (Figure 3.6). Greater dual-task costs for AP ROM ($p < 0.05$) in the obstacle crossing task were also found in YTD children as compared to HYA and OTD children. Moreover, YTD children had greater dual-task costs than HYA for AP ROM ($p < 0.05$) in the level walking task (Figure 3.6a) and greater ML V ($p < 0.05$) than OTD children in the obstacle crossing task (Figure 3.6b). In addition, there was no correlation between the Attention Network scores and dual-task costs for any gait measures ($p > 0.05$).

For gait performance, YTD children showed greater dual-task costs than HYA and OTD children for gait velocity and stride time ($p < 0.05$) in the level walking and the obstacle crossing tasks (Figure 3.6). Greater dual-task costs for stride length ($p< 0.01$) in the obstacle crossing task were also found in YTD children as compared to HYA and OTD children. Moreover, YTD children had greater dual-task costs than HYA for stride length in the level walking task (Figure 3.6a).



A)



B)

Figure 3.6. 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, TTD = trailing toe distance, TTOC = trailing toe obstacle clearance, LTOC = leading toe obstacle clearance, LHD = leasing heel distance), verbal reaction time (VRT) and accuracy in younger and older children with typical development (YTD and OTD) and in healthy young adults (HYA) during level walking (A) and obstacle crossing (B). *Significant difference between YTD children and OTD children. #Significant difference between YTD children and HYA. $Significant difference between OTD children and HYA.

There was no significant difference in dual-task costs for VRT between groups and between tasks. For accuracy, OTD children showed greater dual-task costs than HYA in the level walking and the obstacle crossing tasks ($p < 0.05$) where as YTD children showed greater dual-task costs than HYA only in the obstacle crossing task ($p = 0.05$). Dual-task costs were not significantly different among groups for other measures in both level walking and obstacle crossing tasks ($p > 0.05$) (Figure 3.6).

Discussion

The present study examined the effect of dual tasking on gait performance among YTD children, OTD children and HYA. Our findings revealed that dual task interference with gait performance was found in YTD and OTD children, but it was not found in HYA. In general, gait performance decrements under dual task contexts were greater in YTD than OTD children. Moreover, the results of the present study supported our hypotheses that dual task interference would be lowest in HYA and highest in YTD children when compared among YTD children, OTD children and HYA. In addition, dual task interference with gait performance in YTD children was greater than OTD children, suggesting that there was a developmental trend in attentional resources required to control gait in children with typical development.

The results were consistent with previous studies exploring dual task control in children (Cherng, Liang, Hwang, & Chen, 2007; Huang, Mercer, & Thorpe, 2003), in showing that gait control in children with typical development requires attentional resources to maintain stability. Huang et al (2003) examined dual task effects on gait performance in children aged 5 to 7.8 years by using a visual identification, an auditory identification and a memorization task as the secondary cognitive task. The results showed a decrease in gait velocity for all concurrent cognitive tasks. In particular, the simultaneous performance of walking and either a visual or an auditory identification task decreased cadence and step length (Huang, Mercer, & Thorpe, 2003). Additionally, Cherng 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 either repeating a series of numbers forwards or backwards (Cherng, Liang, Hwang, & Chen, 2007).

Interestingly, the present study found that ML ROM and ML V were not affected by dual tasking. Since balance loss during walking mostly occurs in the ML plane, it is possible that YTD and OTD children 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 Scheaefer et al (2008) on stance balance performance in dual task situations. They found that children aged 9 and 10 years reduced their sway when they were concurrently balancing themselves 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 their stability within narrow margins to protect themselves from falling in dual task situations (Schaefer, Krampe, Lindenberger, & Baltes, 2008).

As mentioned above, YTD and OTD children demonstrated gait performance decrements in other variables during dual task performance. Differences in amount of dual task interference indicated by dual-task costs between YTD and OTD children were found for gait performance in both the level walking task and the obstacle crossing task. As we expected, YTD children showed greater gait performance decrements caused by dual tasking than did OTD children and HYA.

The younger children in the present study were still developing attentional network function, as they showed poorer performance on orienting and conflict scores on the ANT test than OTD, suggesting YTD children have less attentional resources for use in orienting and executive attention subsystems than OTD children. In addition, norms for HYA show that they have the greatest attentional resources among the populations in the present study (Rueda et al., 2004). This suggests that, regarding the assumption of limited resources (Wickens, 1989), children would have fewer available resources for processing the information involved in the two tasks than HYA.

In the level walking task, one reason for the poorer gait performance in the younger children is that they may allow gait instability to be increased, as risk taking in the motor domain is typically a prerequisite for mastering motor skills. As the YTD children in the present study performed at lower levels in the GMFM part E, in walking, running, and jumping, this demonstrates that the YTD group had not reached maturity with respect to these skills. Research has also shown that there are high rates of falls in infants and toddlers as they learn these motorically and attentionally demanding tasks

(Joh & Adolph, 2006). In addition, studies have revealed that falls occurring while walking are one cause of unintentional injury in this young population (Britton, 2005).

When the gait task was increased in difficulty during obstacle crossing, the risk of falls would be also increased. Under this condition, dual-task costs for accuracy were now greater in YTD children than in HYA. In addition, dual-task costs for gait velocity, stride time, stride length and AP V were consistently greater than OTD children and HYA, as they were previously found in the level walking task. Moreover, dual-task costs for trailing toe obstacle clearance were less in YTD children as compared to OTD children and HYA. The results may imply that YTD children who had the smallest available attentional capacity may not have been able to allow additional gait instability to occur as they maintained gait performance at almost the same level as they did in the level walking task. To maintain gait stability, it cost this group on average 7% in cognitive performance decrements. The way that YTD children used cognitive resources for gait postural control was similar to older adults who have deterioration of attentional resources. Doumas et al (2008) demonstrated that older adults had the flexibility in attentional resource allocation to allow additional instability when they were in a relatively stable position. However, when they were in a position that created a higher risk of fall, and which required more attentional resources, they kept allocating attention to posture to maintain stability by not releasing attentional resources to the cognitive task. Thus, the cognitive task performance declined (Doumas, Smolders, & Krampe, 2008).

Moreover, in the difficult gait task, the information processing in YTD children may be more in series than OTD children and HYA as YTD children possibly performed one task at a time (Figure 3.5) to minimize the risk of falls when dual tasking. YTD children responded to the auditory Stroop stimulus after they stepped over an obstacle and took a few additional steps, whereas OTD children 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 is in parallel.

In contrast to YTD children, OTD children do not show the same shifts in allocation of attention, possibly due to their increased attentional resource pool, and/or their strategy of focusing primarily on stability in gait. Thus, they paid more attention to their gait stability than to creating correct responses to the auditory Stroop task, as seen in their reduced accuracy of cognitive performance in the dual task compared to single task conditions in both level waking and obstacle crossing tasks. In addition, the lower accuracy in OTD children may possibly be because they responded earlier than young children as they performed dual tasks (Figure 3.5). These results suggest that OTD children have developed a prioritization for gait postural control, as this "posture first" strategy was also found in healthy young adults and healthy elderly, to avoid hazards and prevent falls while walking (Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001b; Regnaux, Roberston, Smail, Daniel, & Bussel, 2006).

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 performance was less affected than cognitive performance (observed in decreased AP V dual-task costs), 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 a high risk task 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 (Gage, Sleik, Polych, McKenzie, & Brown, 2003).

In conclusion, the results of this study show that YTD children 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 children and HYA. In addition, greater dual task interference is showed in OTD children when compared with HYA. Hence, the ability to control gait stability in dual task conditions is increased with increasing age as attentional resources have increased. In a challenging gait task, our findings demonstrate that children allocate their attention to gait stability more than to the creation of accurate responses to the auditory Stroop task. These findings indicate that children perform what has been called a "postural first" strategy when dealing with a dual task situation, similarly to healthy young adults and the elderly. A knowledge of the cost of performing a concurrent cognitive task on walking and obstacle crossing may help teachers to choose appropriate activities and tools to enhance age-specific motor and cognitive development, while minimizing a risk of accidental falls. Clinicians may use this knowledge regarding TD children's gait and cognitive performance decrements when dual tasking as a norm when evaluating dual task performance of children with developmental delays or deficits.

Bridge

To our knowledge, this was the first study 1) to examine the effects of dual tasking on the development of gait postural control and 2) to determine the extent to which the difficulty of the gait task, (level walking vs. obstacle crossing), affected attentional demands. Our findings demonstrated that YTD and OTD children demonstrated a marked reduction in the ability to perform a gait and a cognitive task simultaneously compared to HYA. In addition, YTD children showed greater dual tasking effects than OTD children on gait performance. When the gait task was increased in difficulty, both YTD and OTD prioritized gait stability over cognitive performance. Moreover, dual tasking interfered less with gait performance than with cognitive performance in the more difficult gait conditions, as seen, for example in a reduction in dual-task costs for AP V in the obstacle crossing as compared to the level walking task.

Chapter IV examines dual task effects on gait and cognitive performance in YTD and OTD children, as well as children with cerebral palsy (CP). It suggests that children with CP, unlike OTD children do not use a "posture first" strategy in dealing with dual task situations.

CHAPTER IV

THE EFFECTS OF DUAL TASK ON POSTURAL CONTROL DURING GAIT IN CHILDERN WITH CEREBRAL PALSY

Drs. P. Dassonville, P. van Donkelaar, L.S. Chou, and M. H. Woollacott helped with the creation of the conceptual design for this experiment. The experimental procedure, including data collection and analysis, described in this chapter was carried out by me. I was the primary contributor to the writing of the research article.

The concurrent performance of a motor task and a cognitive task occurs throughout the activities we perform in our daily lives; for example, when we walk we often are concurrently talking to another person or remembering directions to our destination. The process of learning to walk involves the mastery of a number of motor skills, such as dynamic balance and gait, and the integration between these skills and other attentionally demanding tasks, such as carrying objects, communicating with others, and navigating in a visually complex environment. High rates of falls in typically developing infants and toddlers have been reported as they learn these motorically and attentionally demanding tasks (Joh & Adolph, 2006). In addition, studies have revealed that falls occurring while walking are one cause of unintentional injury in this young population (Britton, 2005).

Balance and gait impairments, including reduced walking speed, and impaired muscle response coordination, have been documented in children with CP (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Hanna et al., 2009; Hsue, Miller, & Su, 2009a, 2009b; Stackhouse et al., 2007). Based on this literature, showing motor system constraints in this population, it could be expected that both performing these activities and coordinating these activities with other motor and cognitive tasks may require additional attentional resources beyond those required of typically developing children who do not have motor impairments. Though falls and injury statistics are unavailable for children with CP, it is likely that, for these reasons, unintentional injury due to falls is even higher in these children who can walk than in the typically developing population.

Research on balance control has shown that neuromuscular deficits are one factor contributing to falls in balance impaired populations. However, recent studies have shown that a second factor contributing to falls is a limitation in attentional resources required for coordinating both balance and secondary cognitive tasks simultaneously (Woollacott & Shumway-Cook, 2002). Falls often occur when not attending to balance while simultaneously performing a second cognitive task. It has thus been hypothesized that most falls are not due to balance deficits in isolation, but to the inability to effectively allocate attention to complex balance tasks or to balance in multitask conditions. It has also been hypothesized that interference between balance and secondary task performance may be apparent in classroom settings, with children with CP showing poor attention to classroom interactions because attentional resources are partially invested in focus on their own stability (Reilly, van Donkelaar, Saavedra, & Woollacott, 2008; Reilly, Woollacott, van Donkelaar, & Saavedra, 2008).

Impairments of cognitive function in children with CP, which have interfered with postural control have also been reported by Reilly et al (Reilly, Woollacott, van Donkelaar, & Saavedra, 2008). The authors noted that children with CP (diplegia and ataxia) showed more sway while standing when simultaneously performing a visual working memory task as compared to standing alone. Children with CP had greater body sway than their peers (older children with typical development, OTD) (7-12 years old), but did not differ from younger children with typical development (YTD) (4-6 years old). In addition, the results showed that children with CP had less visual working memory than children with typical development. Thus, the authors suggested that children with CP had poorer ability to allocate attentional resources to the processing of two attentionally demanding tasks than children with typical development. Consequently, the impairment of postural control and executive function in children with CP led to postural control deficits in a dual task setting.

Even though previous research has shown that there is interference between static postural control and performance of a secondary task in children with CP, the effects of a dual task on gait postural control in these children have not been studied. This raises the question of whether the influences of a concurrent cognitive task (the auditory Stroop task) on gait postural control in children with CP are greater than in children with typical development who are the same age. To answer these questions, the present study was designed to examine gait postural control under dual task conditions in children with CP in comparison with their peers, older children with typical development (OTD), and also with younger children with typical development (YTD) using a dual task paradigm. We hypothesized that attentional requirements for postural control during gait in children with CP would be greater than OTD children, but they would be similar to YTD children.

Methods

Participants

Fifty children were recruited to participate in the study. They were separated into 3 groups including 10 children with spastic cerebral palsy (CP) aged 7-18 years (2 females/8 males; age = 12.17 ± 3.34 years), 20 younger children with typical development (YTD) aged 5-6 years (9 females/11 males; age = 6.22 ± 0.63 years) and 20 older children with typical development (OTD) aged 7-16 years (9 females/11 males; age = 10.92 ± 2.95 years). All children with CP met the following inclusion criteria: 1) diagnosed with spastic cerebral palsy, 2) walking without restrictions or assistive devices (Gross Motor Functional Classification System (GMFCS) level 1-2, and 3) no speech or auditory disability. Three of the children with CP were diagnosed with hemiplegia and the others were diagnosed with diplegia.

Prior to participation in the study, the written and the verbal instructions of the testing procedures were provided to children and their parents or guardians. Informed consent was obtained from parents or guardians, and informed assent was obtained from the children before testing. The study was approved by the Human Subjects Compliance Committee of the University of Oregon. Parents voluntarily completed a Health

Questionnaire to identify the possible injuries and diseases that could affect their child's gait performance. Parents and/or child's teachers also completed the ADHD checklist and Children's Behavioral Checklist to indicate the possibility of cognitive deficits that could affect children's cognitive performance.

All children were examined to determine the level of their motor functional skill performance for walking, running and jumping by using the Gross Motor Function Measure (GMFM-88) (Russell, Rosenbaum, Avery, & Lane, 2002) dimension D (standing) and E (walking, running & jumping) and were also tested for balance ability, and cognitive function using the Pediatric Balance Scale (PBS) (Franjoine, Gunther, & Taylor, 2003), and a child version of the Attentional Network Test (ANT) (Rueda et al., 2004), respectively.

Experiment Equipment

Gait and cognitive performance were measured in the Motor Control Laboratory of the University of Oregon. Three dimensional gait performance was collected by using an eight-camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) at the sample rate of 60 Hz and a fourth-order Butterworth filter with cutoff frequency of 8 Hz. Twenty-nine reflective markers were placed bilaterally on bony landmarks of the child's body. The marker placement has been described in detail elsewhere (Hahn & Chou, 2004; Parker, Osternig, van Donkelaar, & Chou, 2007; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). An auditory Stroop task was used as a secondary cognitive task. Stimuli were relayed to children through two speakers facing the 8-meter walkway. The stimuli which were presented to children included the word “high or “low” spoken with a high or a low pitch. Congruency between pitch and the word were randomized. One infrared-beam which was 45 cm above the ground was set to trigger the initiation of the auditory Stroop task program to ensure that children would hear the stimulus during the swing phase of gait (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008).

Procedures

All children were asked to perform 2 blocks of 4 trials of the seated auditory Stroop task before and after performing a block of level walking task trials. Each trial of the seated Stroop task was composed of 4 stimuli of the spoken word “high” or “low” in a “high” or “low” pitch. The congruence and incongruence between the word and pitch were randomly presented. In a block of trials of the level walking task, children were asked to perform walking on a level surface at their preferred speed for 12 trials in isolation followed by 12 trials with the auditory Stroop task. There was only one stimulus of the spoken word (auditory Stroop task) with random congruency for each walking trial. For the auditory Stroop task, children were instructed to indicate the pitch of the voice as quickly and accurately as possible by saying “high” or “low” while ignoring the actual word that was presented. To counterbalance for possible fatigue and learning effects, half of the children in each YTD and OTD group were asked to first perform a block of level walking trials and then perform a block of obstacle crossing trials. The other half of the TD children were asked to perform the obstacle crossing task before the level walking task. Children were given several practice trials before data collection. In the walking tasks, children wore a safety harness attached to a trolley system secured to the concrete ceiling to prevent injury from an accidental fall. When children were tired or fatigued a pause in the data collection was provided.

Data Processing and Analysis

The15-body segments including head, trunk, 2 upper arms, 2 forearms, 2 hands, pelvis, 2 tights, 2 legs, and 2 feet were used to compute the segmental center of mass locations by the regression equations from Jensen's report (Jensen, 1986). These segmental masses were used to compute the location of the whole-body center of mass (COM) (Winter, 2009). To quantify the child's dynamic stability when walking, the average medial COM-ankle-joint-center inclination angle (Med COM-AJC) throughout the single stance phase of gait was computed. This angle was formed by the intersection between a line from the COM location to ankle joint center, and a vertical line through the ankle joint center in the coronal plane (Silsupadol et al., 2009). In addition, the COM range of motion and the peak linear velocities in the sagittal plane (AP ROM and AP V) and in the coronal plane (ML ROM and ML V) during the crossing stride were also identified.

Temporal-spatial gait parameters, including gait velocity, stride length, stride time, and average step width, were calculated during the crossing stride. Stride length and stride time were determined from the position and the relevant time changes of the heel marker. To eliminate the effect of body size, the distance and velocities parameters were normalized by children's height for all measures except ML ROM and ML V, which were normalized by the distance between right and left anterior superior iliac spine (ASIS width) (Hof, 1996).

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

The amount of dual task interference between gait and cognitive performance was determined by dual-task costs. Dual task costs represented the percentage of performance reductions of each individual's single task performance when performing the two tasks concurrently. Positive values indicate performance decrements in the dual task context, whereas negative values indicate performance improvements from the single to dual task context (Schaefer, Krampe, Lindenberger, & Baltes, 2008). Normalized gait measures, VRT and accuracy were used to calculate dual-task costs in formula (1) for gait velocity, stride length, AP ROM, AP V, and accuracy, and in formula (2) for stride time, step width, ML ROM, ML V, Med COM-AJC, and VRT.

$$((\text{Single} - \text{Dual}) / \text{Single}) \times 100 \qquad \text{-----------------} \ (1)$$

$$((\text{Dual} - \text{Single}) / \text{Single}) \times 100 \qquad \text{-----------------} \ (2)$$

Statistical analyses were performed with SPSS for Windows v.16 (SPSS inc., Chicago, IL). Planned comparisons ANOVA was used to compare baselines balance ability, motor skill and cognitive functional ability between groups of children. Univariate ANOVA with weight mean was used to determined baseline gait and cognitive performance (single task) between groups. To identify the difference of the dual task interference between groups of children, the dual-task costs were examined by using planned comparisons ANOVA.

Results

Baseline Characteristics

Planned comparisons showed that children with CP showed significantly lower performance scores on the PBS and GMFM for dimension D (standing) and E (walking, running and jumping) than YTD and OTD ($p < 0.01$). YTD children showed significantly lower performance scores for the GMFM for dimension E (walking, running and jumping) compared to OTD children ($p = 0.03$). For the Attentional Network Test, YTD performed significantly more poorly than OTD for orienting ($p = 0.04$) and conflict ($p = 0.04$). In contrast, alerting scores was similar for all groups ($p > 0.05$). The children's motor functional ability, balance ability, and cognitive functional ability are showed in Table 4.1.

Baseline Gait Performance

There were differences between groups of children for gait velocity ($F(2, 47) = 4.93$, $p = 0.01$, $\eta^2 = 0.17$), stride length ($F(2, 47) = 9.06$, $p < 0.001$, $\eta^2 = 0.28$), and step width ($F(2, 47) = 3.39$, $p = 0.04$, $\eta^2 = 0.13$). Pairwise comparisons demonstrated that children with CP walked more slowly, with shorter stride length and wider step width than OTD children ($p < 0.05$) (Figure 4.1). In contrast, children with CP walked at a similar speed to YTD children, but their stride length was shorter than YTD children (p =0.01) (Figure 4.1).

Table 4.1. Mean (SE) for Pediatric Balance Scales (PBS), Gross Motor Functional Measures (GMFM) dimension D (standing) and dimension E (walking, running and jumping), and Attentional Network in younger typically developing children (YTD), older typically developing children (OTD), and children with cerebral palsy (CP).

Group	PBS	GMFM		ANT		
		D	E	Orienting	Alerting	Conflict
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 (0.26)	38.70 (0.15)	71.20# (0.33)	56.70# (14.79)	49.68 (15.75)	98.45# (16.82)
CP	51.90* (0.82)	34.50* (0.96)	62.90* (2.41)	39.73 (18.43)	72.95 (19.30)	65.75 (16.53)

*Significant difference between children with CP and YTD/OTD children.
#Significant difference between YTD and OTD children.

Baseline Gait Stability

There were differences between groups of children for AP ROM ($F(2, 47) = 8.97$, $p = 0.001$, $\eta^2 = 0.28$), ML ROM ($F(2, 47) = 10.71$, $p < 0.001$, $\eta^2 = 0.31$), AP V ($F(2, 47) = 4.58$, $p = 0.02$, $\eta^2 = 0.16$), ML V ($F(2, 47) = 9.15$, $p < 0.001$, $\eta^2 = 0.28$) and Med COM-AJC ($F(2, 47) = 5.10$, $p = 0.01$, $\eta^2 = 0.18$). Children with CP demonstrated less AP ROM and slower AP V , greater ML ROM and faster ML V as well as greater Med COM-AJC than OTD children ($p < 0.05$) (Figure 4.2). In addition, children with CP demonstrated similar AP V, ML ROM and ML V, but less AP ROM ($p = 0.01$) than YTD children. Moreover, YTD children performed greater ML ROM and faster ML V than OTD children ($p < 0.05$) (Figure 4.2).

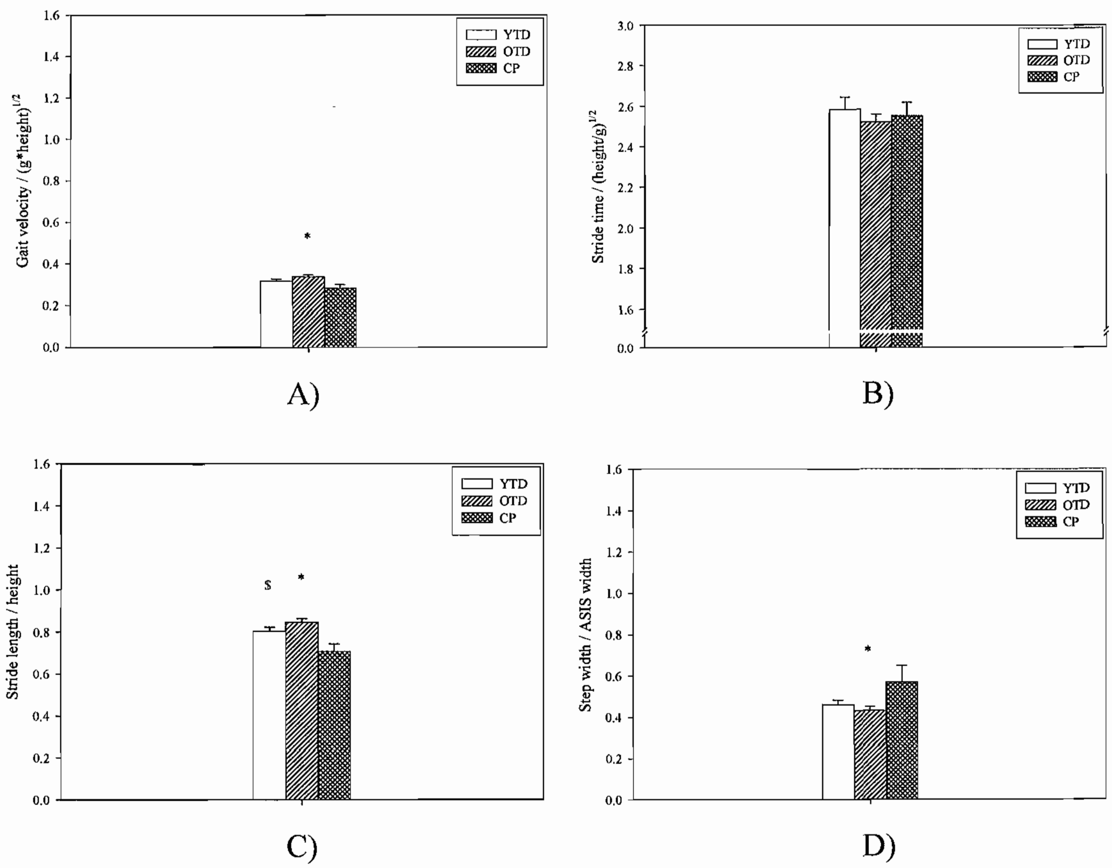


Figure 4.1. Normalized gait velocity (A), stride time (B), stride length (C), and step width (D) for level walking under single dual task conditions in younger and older children with typical development (YTD and OTD) and children with cerebral palsy (CP).*Significant difference between children with CP and OTD children. $Significant difference between YTD children and children with CP.

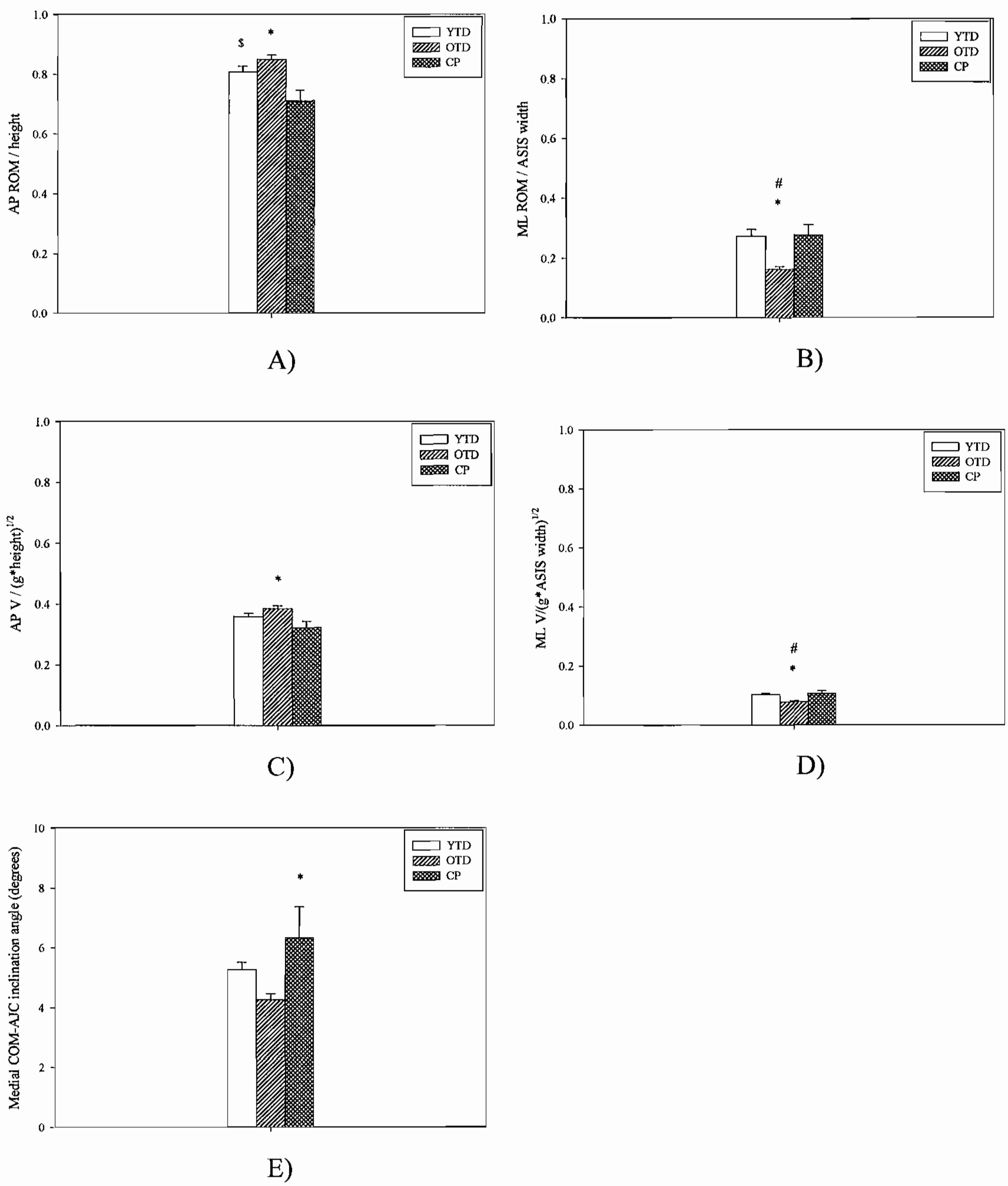
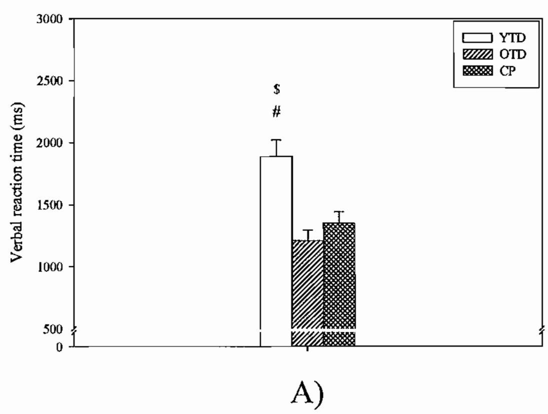


Table 4.2. Normalized center of mass (COM) range of motion in (A) coronal plane (AP ROM) and in (B) sagittall plane (ML ROM), and normalized peak linear velocity of center of mass in (C) coronal plane (AP V), and in (D) sagittal plane (ML V), and (E) medial center of mass-ankle joint center (COM-AJC) inclination angle for level walking under single task conditions in younger and older children with typical development (YTD and OTD) and in children with cerebral palsy (CP). *Significant difference between children with CP and OTD children. #Significant difference between YTD and OTD children. $Significant difference between YTD children and children with CP.

Baseline Cognitive Performance

There were significant differences between groups for verbal reaction time ($F(2, 47) = 11.60$, $p < 0.001$, $\eta^2 = 0.33$) and accuracy ($F(2, 47) = 8.40$, $p < 0.01$, $\eta^2 = 0.26$). Pairwise comparisons revealed that YTD children performed with slower responses and less accuracy than OTD children ($p < 0.001$) and children with CP ($p = 0.01$) (Figure 4.3). OTD children and children with CP did not show significant differences in VRT and accuracy ($p > 0.05$).



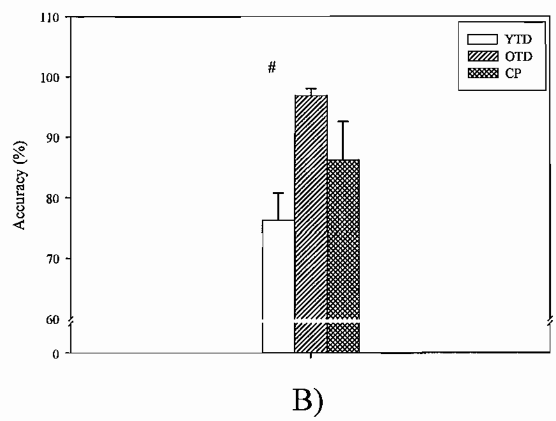


Figure 4.3. Verbal reaction time (A) and accuracy (B) in a single task condition for younger and older children with typical development (YTD and OTD) and in children with cerebral palsy (CP). #Significant difference between YTD and OTD children. $Significant difference between YTD children and children with CP.

Dual-Task Costs

For gait stability, planned comparisons showed that children with CP showed greater dual-task costs for Med COM-AJC than YTD and OTD children ($p < 0.05$) (Figure 4.4). In addition, YTD children showed greater dual-task costs than OTD children for AP V ($p < 0.05$). For gait performance, YTD children showed greater dual-task costs than OTD children for gait velocity and stride time ($p < 0.05$). In contrast to gait performance, OTD children showed greater dual-task costs than children with CP for accuracy ($p < 0.05$).

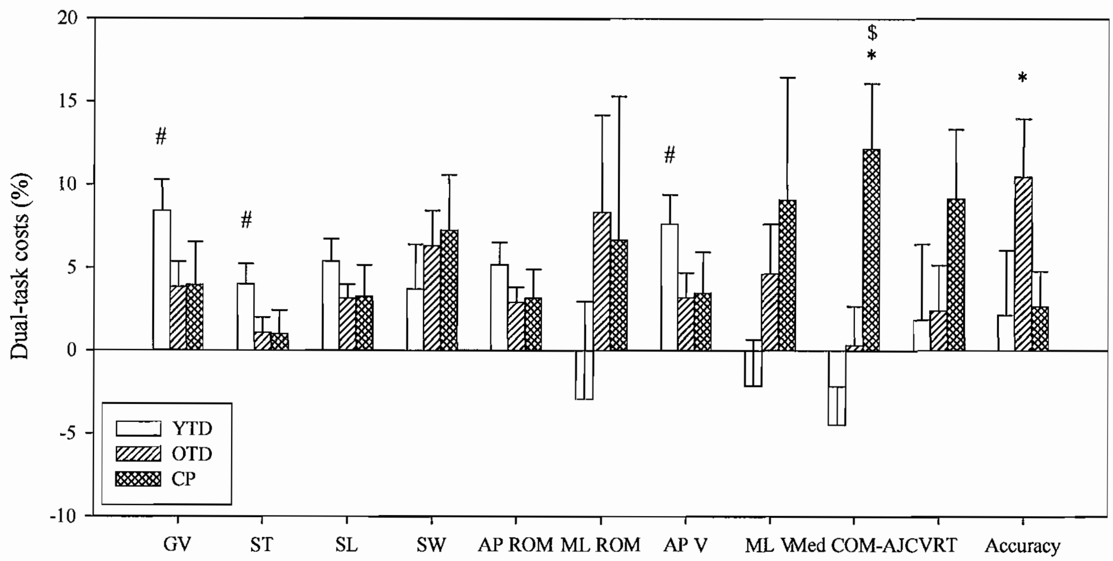


Figure 4.4. Dual-task cost for normalized gait measures (GV = gait velocity, ST = stride time, SL = stride length, SW = step width, AP ROM = anterior-posterior range of motion, ML ROM – medial-lateral range of motion, AP V = peak anterior-posterior linear velocity, ML V = peak medial-lateral linear velocity), medial center of mass-ankle joint center inclination angle (Med COM-AJC), verbal reaction time (VRT) and accuracy in younger and older children with typical development (YTD and OTD), and in children with cerebral palsy (CP). *Significant difference between children with CP and OTD children. #Significant difference between YTD and OTD children. $Significant difference between YTD children and children with CP.

Discussion

The present study aimed to determine if gait control in children with CP who have balance deficits, required increased attentional resources, as compared to that of their age-matched typically developing peers (OTD) children, but similar to YTD children, who have not yet developed mature gait. Our finding revealed that in dual task conditions, children with CP allocated their attention to cognitive performance more than gait stability as was also the case for YTD children. In contrast, OTD children prioritized attention to gait stability more than to accurate performance of the auditory Stroop task.

As expected, children with CP showed slower walking velocity with shorter stride length and wider step width than OTD children. Children with CP also showed less AP ROM and AP V, but greater ML ROM, ML V and medial COM-AJC inclination angle than OTD children, associated with their functional gait impairments. Previous studies have shown that children with CP did not move forward as far as their TD peers when taking a step, and also showed more sway in the medial-lateral direction than their TD peers while walking (Hsue, Miller, & Su, 2009b). The authors suggested that children who had poor control at ankle and hip joints (i.e. lack of push off and hip abductor weakness) could not perform efficient propulsion in walking. Children with CP may use lateral momentum instead of forward momentum to compensate for the lack of ability to generate hip abductor/adductor torque to prevent dropping of the pelvis and trunk of the swing leg side (Hsue, Miller, & Su, 2009b).

Our results revealed that there were significant differences in dual task interference affecting gait performance in the three groups of children. When asked to perform the auditory Stroop task and gait task simultaneously, OTD children showed greater dual-task costs than children with CP for Stroop task accuracy ($p = 0.03$), but children with CP demonstrated greater dual-task costs than OTD and YTD children for medial COM-AJC inclination angle ($p = 0.01$). This increased medio-lateral inclination angle in dual task situations has also been seen in older adults with balance deficits, and may be associated with an increased risk for falls (Silsupadol, et al, 2009). It is of interest that the children with CP did not simply slow gait velocity in the dual task context, which might be considered a strategy to conserve walking safety and reduce the risk for falls, but conserved their single task velocity; thus, dual task interference caused a reduced control of medio-lateral inclination angle during gait or an increased gait instability.

Though there have been no previous published studies on the effect of cognitive tasks on gait characteristics involving children with CP, studies have been performed on patients with hemiplegia due to stroke, who have somewhat similar motor impairments to children with CP. The findings from the studies regarding dual-task paradigms and gait performance in patients with hemiplegia revealed that patients with hemiplegia walked significantly slower and also performed poorer in a cognitive task with dual-task conditions compared to a single-task condition (Canning, Ada, & Paul, 2006; Hyndman, Ashburn, Yardley, & Stack, 2006; Regnaux et al., 2005).

Gait and cognitive performance decrements caused by dual tasking could also be explained by limited available attentional resources (Kahneman, 1973; Wickens, 1989). Simultaneous performance of a walking task and a cognitive task would result in the competition for limited processing resources between the two tasks. These additional demands for attentional resources could exceed the limited attentional capacity of an individual and result in the deterioration of gait and/or cognitive performance.

For patients with stroke, the increase in attentional demands for walking depended on the severity of the walking disability as well as on the available attentional resource capacity (Regnaux et al., 2005). In addition, for children with CP performing a secondary task during quiet standing, there was a negative relationship between the children's executive attentional capacity and the effects of the dual task condition on postural control across all children, including those with CP and those who were TD (Reilly, Woollacott, van Donkelaar, & Saavedra, 2008).

Children with CP in the present study were recruited for their ability to perform the motor tasks of walking, and thus were only mildly impaired in their gross motor functional ability. However, they showed poorer balance control and slightly poorer gait performance (lower scores for the PBS and GMFM) than the YTD and OTD children. Because of their slowed gait velocity, the gait task was substantially easier for them than if it had been performed at the same velocity as their OTD peers. This slower velocity may have contributed to the smaller than expected differences between the two groups in the dual task situation.

In addition, children with CP showed no significant difference in attention performance, as measured by the attention network test, compared to their peers, the OTD children, indicating that they had available the same level of attentional resource performance as their peers. Other dual task research that included children with CP who had documented attention deficits showed that they had greater dual task interference than OTD children when they simultaneously performed a quiet standing task and a visual working memory task (Reilly, Woollacott, van Donkelaar, & Saavedra, 2008). Hence, the mild gait disability, the slower walking velocity, and the lack of limitations of attentional resources in children with CP in this study may have contributed to the significant, but low level of dual task interference as compared to OTD children.

Besides the mildness of gait disability and the lack of limitation of attentional resources, an auditory cognitive task in the present study may not be difficult enough to successfully induce high levels of difference in dual-task costs between OTD children and children with CP, who have the same level of cognitive function. Therefore, competition for using limited information processing resources would be less between this cognitive task and a walking task. Previous research has shown that children with developmental coordination disorder (DCD) who had no known attentional deficits performed similarly with regard to dual task interference as their peers when they were asked to walk with a either an easy or hard concurrent cognitive task (repeating a series of digits forward or backward) (Cherng, Liang, Chen, & Chen, 2009). However, when the secondary task was changed to a difficult motor task (carrying a tray with marbles) which required visual monitoring, greater gait performance decrements were shown in children with DCD in comparison with their peers. Hence, the type of secondary task should be considered as an important factor in contributing to high levels of dual task interference between participants who have equal attentional resources, but unequal motor ability.

We conclude that dual tasking differently interfered with gait and cognitive performance among the groups of children tested. In children with CP and YTD children, dual task interference with gait stability and performance was greater than cognitive performance, as shown by the greater dual-task costs for medial COM-AJC inclination angle that were found in children with CP and the greater dual-task costs for gait velocity, stride time, and AP V that were found in YTD children, as compared to OTD children. In contrast, greater cognitive performance decrements were demonstrated in OTD children (accuracy) as compared to children with CP. Therefore, this suggests that OTD children allocate a greater portion of their attentional resources to maintaining gait stability whereas children with CP and YTD children do not. When they were in the dual task situation OTD children, as has been shown in previous studies for healthy young adults and participants with balance impairment, prioritized gait stability over the cognitive tasks, presumably to prevent falls (Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001b; Brauer, Woollacott, & Shumway-Cook, 2002). In contrast, children with CP, who had balance deficits, may not have been able to appropriately deal with the dual task situation as they did not prioritize gait stability as OTD children did. This implies that the risks of falls in children with CP were increased because of their risky behaviors of not prioritizing gait stability.

YTD children, who had not reached maturity with respect to gait and cognitive performance (they showed lower levels in the GMFM part E, in walking, running, and jumping, and poorer attention performance), may have simply had less attentional resources available to them than OTD children, or they may have allocated less attention to the gait task than to the cognitive task, since risk taking in the motor domain is typically a prerequisite for mastering motor skills and typical of younger children. High rates of falls in infants and toddlers have been reported as they learn these motorically and attentionally demanding tasks (Joh & Adolph, 2006). In addition, falls occurring while walking are one cause of unintentional injury in this young population (Britton, 2005). Moreover, YTD children may have flexibly allocated attention between the two tasks, seeing that the dual task costs were taken from the gait task in the relative stable posture (i.e. level walking), which could create additional instability. They dealt with the more difficult postural task by reducing cognitive performance, possibly because they were now at their limits of stability in the obstacle crossing task. This type of result was also found in older adults who had deterioration of attentional resources (Doumas, Smolders, & Krampe, 2008)

In summary, the results of this study suggest that children with CP, who have high mild impairments in motor functional ability and normal attentional performance levels, and YTD children, who have not reached maturity with regard to gait and cognitive performance, unlike OTD children, do not use a "posture first" strategy in dealing with dual task situations. Consequently, children with CP and YTD children would have a high risk of falling when they are in a complex environment. In order to differentiate children with CP and TD children by using the dual task paradigm, the type of a secondary task is an important factor for successfully increasing the competition for attentional resource sharing. Finally, regarding clinical applications of attention and gait control in children with CP, clinicians and educators should consider the severity of the pathology as well as the attentional ability of the individual in order to select efficient tools for examination and rehabilitation of motor function.

Bridge

The effects of dual tasking on gait postural control in children with CP were investigated. Results support the conclusion that dual tasking interfered with gait and cognitive performance in all children with CP and TD children. However, unlike OTD children, YTD children and children with CP used a different strategy to cope with dual tasking. They did not prioritize their attention to gait. Hence, the risk of falls could be increased, especially in children with CP, who increased medio-lateral inclination angles during walking in the dual task condition, thus increasing their instability in gait.

Chapter V summarizes the conclusions drawn from the major findings of each experiment and provides a general discussion of this study. The following chapter further offers suggestions for how this research might be applied to the assessment and treatment of children with CP.

CHAPTER V

DISCUSSION

The prior summary of the research literature related to postural control during gait has shown that gait control requires attentional resources in children and adult populations (Cherng, Liang, Hwang, & Chen, 2007; Ebersbach, Dimitrijevic, & Poewe, 1995; Huang, Mercer, & Thorpe, 2003; Lajoie, Teasdale, Bard, & Fleury, 1993; Lindenberger, Marsiske, & Baltes, 2000). However, research exploring changes in the attention requirements of gait postural control during development in typically development (TD) children or children with cerebral palsy (CP) has not been clearly shown. In addition, a primary reason for balance loss during locomotion is a trip or a slip. There is no research characterizing developmental changes in the ability to maintain and recover stability during perturbed locomotion (for example, obstacle clearance tasks) in dual task conditions. The purpose of the study was to examine 1) the development of postural control during gait in TD children while performing a cognitive task (the auditory Stroop task) and a gait task simultaneously, 2) the attentional requirements of gait postural control when the difficulty of the gait postural control task was increased, as in an obstacle crossing task, and 3) the influences of a concurrent cognitive task (the auditory Stroop task) on gait postural control in children with CP.

The first study investigated typical development of gait postural control in younger and older children (YTD and OTD) during two gait tasks, including a level walking task and an obstacle crossing task, using a dual task paradigm, and compared the results of the children's performance with that of healthy young adults (HYA) from the study of Siu et al (2008) (Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). Our findings revealed that gait control in TD children requires attentional resources to maintain stability. Moreover, the results also demonstrated that dual task interference was less in HYA as compared to YTD and OTD children. Gait performance decrements in the dual task context were greater in YTD children as compared to OTD children, whereas cognitive performance decrements in YTD and OTD children were similar. In addition, dual tasking affected cognitive performance more in YTD children when the difficulty of the gait task was increased. The results suggested that there was a developmental trend in attentional resources required to control gait in children with typical development. Gait postural control under dual task conditions was improved when children were more mature, as their attention resources increased with age.

The results raise the question of why, in level walking with a concurrent auditory Stroop task, YTD children showed interference with gait more than cognitive performance whereas OTD children showed interference with cognitive performance more than gait performance. As YTD children had not reached maturity for either gait or cognitive performance, one possible explanation was that YTD children, who have less attentional capacity, may have flexibly allocated attention, seeing that they allowed additional instability to gait in a relative stable posture (i.e. level walking). However, when the difficulty of the gait task was increased, YTD children did not (or possibly could not) allow instability to be further increased, as they still allocated almost the same amount of attentional resources to gait stability as they did in the easy gait task. Consequently, their cognitive performance declined. The way that resources were shared in YTD children, in easy vs. difficult postural tasks, has also been found in older adults who had a deterioration of attentional resources (Doumas, Smolders, & Krampe, 2008). In addition, YTD children may take more risks in the motor domain since it is typically a prerequisite for mastering motor skills, as high rates of falls in infants and toddlers have been reported as they learn these motorically and attentionally demanding tasks (Joh & Adolph, 2006). Another possible explanation was that OTD children may develop the "posture first" strategy to prevent falls and hazard accidents. This strategy has been found in healthy young adults and healthy elderly (Bloem, Grimbergen, van Dijk, & Munneke, 2006; Regnaux, Roberston, Smail, Daniel, & Bussel, 2006).

The final study investigated the attentional requirements for postural control during gait in children with CP compared to YTD and OTD children. Our results demonstrated that dual task interference in children with CP was similar to that of YTD children in that both groups showed gait performance decrements. In contrast, OTD children demonstrated greater cognitive performance decrements than children with CP. Thus, children with CP like YTD children do not prioritize gait stability in the dual task situation. This may lead to an increased fall risk in these populations. It is of interest that the children with CP did not slow gait velocity in the dual task context, as the YTD children did, but instead showed an increased medio-lateral inclination angle. This increased medio-lateral inclination angle in dual task situations has also been seen in older adults with balance deficits, and may be associated with an increased risk for falls (Silsupadol et al., 2009).

However, the level of difference in dual task interference between children with CP and OTD children was low, seeing that only one gait parameter, the medial center of mass-ankle joint center inclination angle, was different between these two groups. What could be factors contributing to these results?

Factors contributing to the results could be 1) the low levels of severity of walking disability in the children with CP and the fact that they walked even in the single task situation with a reduced velocity compared to the OTD children, thus making the difficulty of the walking tasks less for the children with CP, 2) the fact that the children with CP had normal attentional resource capacity for their age, as well as 3) the type of a secondary task used to study attentional demands for gait control. Though there is no research on dual task effects on postural control during gait in children with CP, previous research has reported that dual task interference with quiet stance postural control in children with CP showed a negative relationship with executive attentional capacity (Reilly, Woollacott, van Donkelaar, & Saavedra, 2008). In addition, research done in patients with stroke, who have somewhat similar motor impairments to children with CP, demonstrated that increased attentional demands for walking depended on the available attentional resource capacity as well as on the severity of the walking disability of the individual (Regnaux et al., 2005).

Thus, children with CP in this study who had mild gait disability and a lack of limitations of attentional resources could be expected to show smaller significant differences from their OTD peers in dual tasking effects than children with more severe disabilities. Moreover, an auditory cognitive task in the present study may not have been difficult enough to successfully induce high levels of difference in dual-task costs between OTD children and children with CP, who have the same level of cognitive function. Therefore, to be able to discriminate between different groups of children with CP who have a broad range of levels of impairment, and their TD peers, it would be useful to incorporate into the dual task paradigm a type of secondary task with varying degrees of difficulty (for example, the N-back task).

Clinical Implication

Previous studies have revealed that gait and cognitive decrements associated with dual tasking were found in typically developing children as well as healthy young adults (Cherng, Liang, Hwang, & Chen, 2007; Huang, Mercer, & Thorpe, 2003). Besides dual task interference with gait and cognitive performance in children, our findings in chapter III demonstrated that the dual task interference with gait performance, as determined by dual-task costs, was greater in YTD children as compared with OTD children. When YTD children were involved in a more difficult task, they demonstrated an improvement in their gait stability, but a decline in their cognitive task performance.

In addition, children have shown the development of the "posture first" strategy, which has also been found in healthy young adults and healthy elderly (Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001a; Regnaux, Roberston, Smail, Daniel, & Bussel, 2006). This study provides clinicians and teachers an understanding of how age-related differences in gait and cognitive ability influence a child's gait and cognitive performance in isolation (gait or cognitive task performed alone) and also how they differentially affect a child's ability to perform cognitive and motor tasks simultaneously.

Moreover, we found that the mildness of gait disability, the slower walking velocity in children with CP, and the lack of limitation of attentional resources as well as types of secondary tasks may be important issues to consider when evaluating postural control during gait under dual task conditions in participants who have a similarity in attentional capacity, but difference in motor ability as described in chapter IV. Thus, clinicians and teachers should not consider only the intrinsic factors such as individuals' severity of motor disability and attentional ability, but also extrinsic factors like the difficulty of the primary gait task and secondary task in order to select efficient tools for examination and rehabilitation of motor function in the clinical and school setting. The clinical assessments and rehabilitation programs for postural control during gait should include varying difficulty levels of the secondary task and primary gait task which should correspond to the individual motor skills or severity levels of the motor disability.

Limitations of the Study

The first limitation of the study was the small sample size of healthy young adults and children with CP group in this study (n =12 and 10 respectively). We did not collect data in healthy young adults ourselves; we used the data from a previous study using the same protocol, from our laboratory. In children with CP, we wanted to recruit more participants to obtain a good representation of the population. However, the inclusion criteria for children with CP in this study were very strict, as they had to walk independently and have no speech or auditory deficits, in order to perform the auditory Stroop task. It was very difficult to get a large portion of children with CP who met these inclusion criteria, who were willing to complete all testing sessions of the experiment and whose parents were willing to bring them to the laboratory. However, I believe this sample size was enough to clearly represent the population, as significant differences were found between TD children and healthy young adults, and between TD children and children with CP.

A second limitation was the individual differences within the group of children with CP and the younger TD children. Each child had a different mental and physical fatigue level. Children may not have fully performed at the highest level of their ability as they felt bored when they had to do the same task repetitively. We minimized this factor by giving them a rest, entertaining them and encouraging them with games and prizes. Thus, this factor may have been minimized to the extent possible through social and behavior support systems.

A third limitation was the difficulty of the auditory Stroop task. YTD children demonstrated some difficulty in understanding the task. We had three younger children who refused to perform the auditory Stroop task because they felt uncomfortable with its difficulty level. We solved this problem by giving YTD children more practice with the task accompanied by their parents' assistance, until they understood and felt comfortable with the task. Consequently, YTD children competently performed the task throughout the experiment and showed consistency of performance.

A fourth limitation was that we did not directly measure attentional capacity, but we measured the attentional performance by using a child's version of the Attentional Network test. In addition, there is no available evidence showing the Attention Network test has a correlation with attentional capacity, though , Redick and Randall (2006) showed that participants with high working memory capacity demonstrated greater performance for the executive control network than participants with low working memory capacity whereas they similarly performed in the orienting and alerting networks (Redick & Randall, 2006). Thus, we could not strongly indicate whether the group differences found in this study were due to differences in attentional capacity, or the amount of attention required for the different task components.

Further Research

Additional studies are needed to investigate differences in postural control during gait in dual task conditions in children with CP and their typically developing peers who have similar cognitive capacity, by using other types of secondary tasks with a variety of levels of difficulty, such as the N-back task, which allows the experimenter to test short term memory for numbers that were presented previously (1 back through n-back) in a sequence. It also might be helpful to use a secondary task involving visual processing, which is also used in gait control, as postural-cognitive task similarity induces dual task interference increments. This type of study would be useful in aiding clinicians in the selection of efficient tools to evaluate and rehabilitate patients with varying motor and attentional deficits, including those who have motor deficits, but lack of limitation of attention capacity.

APPENDIX A

UNIVERSITY OF OREGON INFORMED CONSENT:

TYPICALLY DEVELOPING CHILDREN

Motor Control Laboratory

For sessions with typically developing children

You and your child are invited to participate in a research study being conducted by Dr. Marjorie Woollacott in the Department of Human Physiology at the University of Oregon. As a result of the study we hope to learn more about the underlying neuromuscular mechanisms of balance control in children with cerebral palsy. The results from this study may help us develop appropriate treatments to assist persons with cerebral palsy with their balance. During the course of the study you may come to the laboratory two or three times, if you agree.

During your 2-3 visits (each lasting 45-90 minutes) to the Motor Control Laboratory, your child may be asked to do some of the following things:

1. Walk along an 8-m walkway, step over an obstacle, and continue walking along the walkway, all at a comfortable self-selected speed while barefoot. The height of the obstacle is 10% of your child's height. Your child will wear a safety harness while walking on the walkway so that they will not fall. In addition an adult will stand behind your child during the session to provide assistance.
2. Walk along an 8-m walkway, step over an obstacle, and continue walking along the walkway while doing a second task (for example, telling us if a tone they hear is high or low). Your child will wear a safety harness while walking on the walkway so that they will not fall.
3. Do a cognitive task while sitting (for example, telling us if a tone they hear is high or low, or telling us where a cartoon is on a screen in front of them).

We will also videotape your child's motion in each trial. Several markers will be placed on your child's joints and some body landmarks to help identify joint movements in later videotape analysis. Your child will be asked to wear shorts and sleeveless T-shirts so that the markers can be observed clearly. You will receive a reimbursement of $10 per session. You will be compensated in full, even if you need to terminate participation early.

Potential Risks: There is some risk that your child may begin to fall when his or her balance is disturbed during obstacle crossing. This risk is minimized by using a small wooden dowel which easily comes loose and falls to the ground if bumped by your child's foot, using a safety harness to catch your child if he/she should fall, providing a handrail to grasp, and keeping an attendant near you. The risk of getting a skin response to the application of sensors will be minimized by using hypoallergenic gel and tape. The incidence of a skin response to the gel and tape is actually low or non-existent. There is another risk that your child may become tired or uncomfortable during some of the tasks. This risk is minimized by providing rest periods or by stopping the test at your or your child's request. There is also a risk of losing confidentiality of information. This is minimized by coding all data with letters and numbers and keeping all participants' names on a separate sheet available only to the investigators directly involves with this study.

Any information that is obtained in connection with this study and that can be identified with you or your child will remain confidential and will be disclosed only with your permission. Data will be kept indefinitely. We may wish to use the video tape recording, or pictures of your child's movements for research and educational purposes in the future. In such cases your child would be referred to only by code, and your child's identity would not be disclosed. In addition your child's facial features will be obscured as much as possible on photos or videotapes to maintain confidentiality. If you would like to give your permission for the use of this tape recording or pictures for research and educational purposes, please place your initials by "yes." If you do not wish to give permission, please place your initials by "no."

Yes______________ No______________

All instrumentation and procedures have been thoroughly checked prior to this test session and any potential risks have been explained. At any time you may ask questions or terminate your (your child's) participation.

You will be with your child at all times and you may stop the testing at any time. You may also ask questions at any time. If you have any questions at any time, you may call the project director Dr. Marjorie Woollacott at (541) 346-4144. If you have any questions about your (your child's) rights as a participant in a research project, you can call the Human Subjects Compliance Office, University of Oregon (541) 346-2510.

Your participation is voluntary and your decision as to whether or not to participate will not affect your (your child's) relationship with the Child Development and Rehabilitation Center or the Motor Control Lab at the University of Oregon. Your signature below indicates that you have read and understand the information provided above and indicates your willingness to participate. However, it is your right to withdraw at any time without penalty or loss of benefits to which you or your child are otherwise entitled. By signing this form you are not waiving any legal claims, rights or remedies. A copy of this form will be yours to keep.

______________________________	______________________________
Signature (Parent/Legal Guardian)	Date
______________________________	______________________________
Child's name	Child's birth date
______________________________	______________________________
Signature of witness	Date

APPENDIX B

UNIVERSITY OF OREGON INFORMED CONSENT:

CHILDREN WITH CEREBRAL PALSY

Motor Control Laboratory

For sessions with children with cerebral palsy

You and your child are invited to participate in a research study being conducted by Dr. Marjorie Woollacott in the Department of Human Physiology at the University of Oregon. As a result of the study we hope to learn more about the underlying neuromuscular mechanisms of balance control in children with cerebral palsy. The results from this study may help us develop appropriate treatments to assist persons with cerebral palsy with their balance. During the course of the study you may come to the laboratory two or three times, if you agree. We also may evaluate your child in another setting (for example, their school or clinic).

If you and your child decide to participate, he/she will receive a neurological and musculoskeletal exam by Dr. Robert Nickel or another physician of the Child Development and Rehabilitation Center (CDRC) at the University of Oregon. We expect that the clinical visit will take approximately 30-45 minutes.

You will not be responsible for the payment related to your examination by the physician under this study. Any information that is obtained in connection with this clinical visit will remain confidential and will be disclosed only with your permission as granted in this consent form and its attachment. In order to do this research, you must also authorize us to access and use the above health information. An authorization form to allow the physician to release that health information is attached for you to review and sign as an addendum to this consent form. Another form also requests authorization to receive information from your child's pediatrician.

During your 2-3 visits (each lasting 45-90 minutes) to the Motor Control Laboratory, your child may be asked to do some of the following things:

1. Walk along an 8-m walkway, all at a comfortable self-selected speed while barefoot. The height of the obstacle is 10% of your child's height. Your child will wear a safety harness while walking on the walkway so that they will not fall. In addition an adult will stand behind your child during the session to provide assistance.

2. Walk along an 8-m walkway while doing a second task (for example, telling us if a tone they hear is high or low). Your child will wear a safety harness while walking on the walkway so that they will not fall.
3. Do a cognitive task while sitting (for example, telling us if a tone they hear is high or low, or telling us where a cartoon is on a screen in front of them).

We will also videotape your child's motion in each trial. Several markers will be placed on your child's joints and somebody landmarks to help identify joint movements in later videotape analysis. Your child will be asked to wear shorts and sleeveless T-shirts so that the markers can be observed clearly. You will receive a reimbursement of $.32 per mile for each trip and $50 for completion of each laboratory session or $10 for completion of each clinical test session. You will be compensated in full, even if you need to terminate participation early.

Potential Risks: There is some risk that your child may begin to fall when his or her balance is disturbed during obstacle crossing. This risk is minimized by using a small wooden dowel which easily comes loose and falls to the ground if bumped by your child's foot, using a safety harness to catch your child if he/she should fall, and keeping an attendant near him/her. The risk of getting a skin response to the application of sensors will be minimized by using hypoallergenic gel and tape. The incidence of a skin response to the gel and tape is actually low or non-existent. There is another risk that your child may become tired or uncomfortable during some of the tasks. This risk is minimized by providing rest periods or by stopping the test at your or your child's request. There is also a risk of losing confidentiality of information. This is minimized by coding all data with letters and numbers and keeping all participants' names on a separate sheet available only to the investigators directly involves with this study.

Any information that is obtained in connection with this study and that can be identified with you or your child will remain confidential and will be disclosed only with your permission. Data will be kept indefinitely. We may wish to use the video tape recording, or pictures of your child's movements for research and educational purposes in the future. In such cases your child would be referred to only by code, and your child's identity would not be disclosed. . In addition your child's facial features will be obscured as much as possible on photos or videotapes to maintain confidentiality. If you would like to give your permission for the use of this tape recording or pictures for research and educational purposes, please place your initials by "yes." If you do not wish to give permission, please place your initials by "no."

Yes______________ No______________

All instrumentation and procedures have been thoroughly checked prior to this test session and any potential risks have been explained. At any time you may ask questions or terminate your (your child's) participation.

You may be with your child at all times and you may stop the testing at any time. You may also ask questions at any time. If you have any questions at any time, you may call the project director Dr. Marjorie Woollacott at (541) 346-4144. If you have any questions about your (your child's) rights as a participant in a research project, you can call the Human Subjects Compliance Office, University of Oregon (541) 346-2510.

Your participation is voluntary and your decision as to whether or not to participate will not affect your (your child's) relationship with their medical provider or the Motor Control Lab at the University of Oregon. Your signature below indicates that you have read and understand the information provided above and indicates your willingness to participate. However, it is your right to withdraw at any time without penalty or loss of benefits to which you or your child are otherwise entitled. By signing this form you are not waiving any legal claims, rights or remedies. A copy of this form will be yours to keep.

Signature (Parent/Legal Guardian)	Date
Child's name	Child's birth date
Signature of witness	Date

APPENDIX C

UNIVERSITY OF OREGON ASSENT FORM

Constraints on Dynamic Balance Control in Children with Cerebral Palsy

We are doing a study to see if we can better understand balance problems in children with cerebral palsy.

You will come to the clinic and/or lab about 2-3 times for about 45-90 minutes each. We'll measure how you ***walk and/or step over obstacle.*** *Sometimes will ask you to do these when you are doing something else, like listening or watching a screen. We might also ask you to reach for something while sitting or standing. We will have you will wear a safety harness while you walk so that you do not fall.* ***We will be putting small markers on different parts of your leg, arms, head and trunk in order see how you move.*** *You will be able to sit down and rest as often as you need to during your balance testing.*

You don't have to be in this study if you don't want to. You can change your mind any time and not come back to the clinic for balance testing. We'll answer all of your questions any time.

Do you have any questions? Is this OK with you? If this is OK with you, sign below.

Signature of child ________________________________ *Date* ____________

Signature of parent/legal guardian ____________________ *Date* ____________

Investigator's signature ___________________________ *Date* ____________

Copies to: Subject/Parent
Medical Record (when appropriate)

APPENDIX D

AUTHORIZATION FORM FOR RESEARCH DISCLOSURE OF PERSONAL HEALTH INFORMATION (#1)

By my signature below, I authorize Robert Nickel, MD or other evaluating physician from Child Development and Rehabilitation Center (CDRC), to release to Sujitra Boonyong and Dr. Marjorie Woollacott at the University of Oregon the following records related to my child's history of cerebral palsy: neurological and musculoskeletal examination results, documentation of any deficits in sensory motor functions, and documentation of any behavioral and cognitive functions.

They will use these medical records containing my child's personal health information to help them determining the contributions of specific impairments to my child's motor abilities. This authorization will expire at the end of the research study.

I understand that this authorization can be revoked at any time by delivering a revocation in writing to the Health Care Provider named above and that the revocation will be effective except to the extent (1) research has already been conducted in reliance on my previous authorization or (2) if necessary to protect the integrity of the research (e.g., to account for a person's withdrawal from the research).

I realize that Dr. Marjorie Woollacott and Sujitra Boonyong may not be bound by the Privacy Rule and therefore may not be required by that Rule to maintain the confidentiality of my child's personal health information. However, they can only use or disclose my child's health information for purposes approved by the Institutional Review Board at the University of Oregon or as required by law or regulations and will continue to protect my child's personally identifiable health information as described in the attached Informed Consent Form.

I understand what this document says and authorize the release of my child's personal health information as stated above; I understand I will be given a signed copy of this Authorization for my records.

For Minor subjects: Name of Minor____

_______________________________________ ____________________________
Signature of Legally Authorized Representative Date

____________________________________ _____________________________
Print Name Relationship of representative to subject

APPENDIX E

AUTHORIZATION FORM FOR RESEARCH DISCLOSURE OF PERSONAL HEALTH INFORMATION (#2)

By my signature below, I authorize my child's teacher, ____________________, to release to Dr. Marjorie Woollacott and Sujitra Boonyong at the University of Oregon, and Robert Nickel, MD or other evaluating physician from Child Development and Rehabilitation Center (CDRC) the following records related to my child's behavior: 1) name, 2) address, 3) academic performance, 4) achievement test score, IQ, readiness or aptitude test scores, and 5) social performance.

They will use these behavioral records containing my child's personal behavior information to help them determining the contributions of behavior and attention to my child's motor abilities. This authorization will expire at the end of the research study.

I understand that this authorization can be revoked at any time by delivering a revocation in writing to the teacher named above and that the revocation will be effective except to the extent (1) research has already been conducted in reliance on my previous authorization or (2) if necessary to protect the integrity of the research (e.g., to account for a person's withdrawal from the research).

I realize that Dr. Marjorie Woollacott and Ms. Sujitra Boonyong may not be bound by the Privacy Rule and therefore may not be required by that Rule to maintain the confidentiality of my child's personal behavior information. However, she can only use or disclose my child's behavior information for purposes approved by the Institutional Review Board at the University of Oregon or as required by law or regulations and will continue to protect my child's personally identifiable health information as described in the attached Informed Consent Form.

I understand what this document says and authorize the release of my child's personal health information as stated above; I understand I will be given a signed copy of this Authorization for my records.

For Minor subjects: Name of Minor ____

____	______________________________
Signature of Legally Authorized Representative	Date
____	______________________________
Print Name	Relationship of representative to subject

APPENDIX F

UNIVERSITY OF OREGON HEALTH QUESTIONNAIRE

Motor Control Laboratory

You and your child have agreed to participate in the research study conducted by Sujitra Boonyong, PT and Dr. Marjorie Woollacott. As a result of this study we hope to learn about the underlying neuromuscular mechanisms involved in balance control and cognitive ability not only in the developing child, but in children with neurological impairments. The following birth history and health information is needed to complete the study. This information will be kept confidential and will be used only for the purpose of this research.

Subject #: __________________Birth date: (mm/dd/yyyy)__________________

1. Birth History:

Did you or your child have any problems during the birthing process?

Circle One: Yes No A Little Comments:

____

____

____

2. Developmental History: Please indicate the approximate age at which your child learned the following skills.

	Months
Crawl on hands and knees	
Sit independently when placed	
Walk independently	
Ride a tricycle	
Jump with both feet	
Ride a bicycle (2 wheeler)	

Do you have any concerns about how your child moves or about his or her coordination?

Circle One: Yes No A Little Comments:

____

____

____

3. Medical History:

Has your child had any surgeries, hospitalizations or major illnesses?

Circle One: Yes No A Little Comments:

____

____

____

____

Medications: Does you child take medications for any of the following conditions?

	Yes	**No**
Seizure disorder	*	
Attention Deficit Disorder	*	

*Comment____

____

____

4. Behavior:

Do you have any concerns about how your child gets along with others?

Circle One: Yes No A Little Comments:

____

____

____

5. Learning:

Has your child ever been diagnosed with a cognitive impairment (i.e. Attention Deficit Hyperactivity Disorder (**ADHD), dyslexia, etc)?**

Circle One: Yes No A Little Comments:

____

____

____

Do you have any concerns about how your child is learning new skills in preschool or school?

Circle One: Yes No A Little Comments:

____

____

____

6. Activities:
Does your child participate in any of the following movement activities on a regular basis?

Dance
Ball sports (soccer, football, baseball tennis, etc.)
Gymnastics
Martial Arts

Comment:

Parent/Guardian Signature

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