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Gait in attention deficit hyperactivity disorder

Effects of methylphenidate and dual tasking

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Abstract *Background* Cognitive function and the loading of attention presumably play an important role in gait as well as in fall risk, but previous work has not demonstrated this in any cause-and-effect way. *Objectives* To gain insight into the relationship between gait and cognitive function, we sought: (1) To compare the gait rhythmicity (stride time variability) of children with attention deficit hyperactivity disorder (ADHD) to controls, (2) To test the hypothesis that dual tasking leads to increased stride-to-stride variability in ADHD, and (3) To test whether pharmacological treatment that relieves ADHD symptoms reduces stride-to-stride variability. *Patients and Methods* Gait was quantified in children with ADHD and in age-matched healthy controls under single task and dual task conditions on three occasions: off medications (both groups) and, in the ADHD group, after double blinded, randomized administration of methylphenidate (MPH) or placebo. *Results* At baseline, children with ADHD tended to walk with increased stride-to-stride variability compared to the controls during the single task condition ($p = 0.09$). During dual task walking, stride time variability was significantly reduced in the children with ADHD ($p < 0.004$), but not in the controls. In the children with ADHD, the placebo did not significantly affect stride-to-stride variability or the dual tasking response. In contrast, stride time variability was significantly reduced on MPH ($p < 0.001$) such that dual tasking no longer affected variability. *Conclusions* The present findings demonstrate alterations in the gait of children with ADHD, support a cause and effect link between cognitive function and gait, and suggest that enhancement of attention abilities may, in certain populations, improve gait rhythmicity.

Key words gait · attention · dual task · cognitive function · ADHD

Introduction

Investigations using dual tasking paradigms have demonstrated that the neural control system responsible for the regulation of gait apparently relies on cognitive input [1]. When healthy adults, irrespective of age, are asked to walk and perform an attention demanding "dual task" simultaneously, they generally slow down (i.e., walk with a reduced gait speed) [2, 3]. The impact of dual tasking is even more profound among older adults with Parkinson's disease, Alzheimer's disease or idiopathic elderly fallers [3–7]: gait slows down, and in addition, the stride-to-stride variability of gait timing markedly increases. Stride-to-stride variability reflects the regularity, rhythmicity, and automaticty of gait and is associated with fall risk in many populations [8–12]. Interestingly, in addition to sharing an increased risk of falling [9, 13, 14], these patient groups all display deficits in specific cognitive domains that have been related to dual tasking abilities, including executive function and attention, and the degree of the response to dual tasking has been correlated with these cognitive deficits [3, 6, 7]. One interpretation of these findings is that in patients with diminished gait automaticty (i.e., increased variability) supplementary cognitive resources, such as attention, are needed to regulate the stride-to-stride variations in gait. When this abnormal motor background is combined with a reduced capacity to divide attention among multiple tasks (i.e., deficits in executive function and attention), an attention demanding task may bring about an additional increase in stride time variability and gait inconsistency that exacerbates the risk of falling.

Study of children with attention deficit hyperactivity disorder (ADHD) offers a unique opportunity to further probe the contribution of attention to gait. ADHD is the most prevalent neuro-behavioral disorder of childhood. Problems with attention are among its core symptoms, making it an ideal cohort for studying the role of this cognitive domain in gait. Patho-physiologically, ADHD is assumed to be the result of dopaminergic depletion [15, 16], somewhat reminiscent of the dopamine deficits that are the hallmark of Parkinson's disease. Both anatomic and functional neuro-imaging studies have demonstrated that children and adults with ADHD have reduced volumes and metabolic rates in specific brain areas including the caudate nucleus, frontal lobes and the prefrontal cortex, the latter two being areas in the brain that play an especially important role in executive function and attention [15, 17, 18]. Medications like methylphenidate (MPH) and dextroamphetamines have been the mainstay of the medical therapy of the disorder [19]. These medications are assumed to increase the availability of cathecholamines in the synaptic cleft, thereby reversing some of the symptoms and enhancing performance on tasks that require attention [19–23].

Many studies have demonstrated that subjects with ADHD have quantifiable deficits in executive function and attention [24–29], however, the relationships between these deficits, gait automaticity, and dual tasking have not been studied. While children with ADHD do not complain of falls, they are more prone to injury [30], perhaps as a result of subtle deficits in gait and/or the ability to focus on walking. Given the known deficits in attention in ADHD and the evidence suggesting that the regulation of stride time variability requires attention, we sought to investigate the gait of those with ADHD and to use this cohort to examine the role of attention in gait and the effects of pharmacology on that relationship. More specifically, we tested the following hypotheses in order to gain insight into the cognitive demands of usual walking and the effects of ADHD on this routine activity of daily living: (1) that at baseline (i.e., in an unmedicated state), children with ADHD would walk with an increased stride time variability compared to age-matched controls, (2) that an attention-demanding, dual task would further increase the stride time variability of the ADHD group, and (3) that MPH would reduce the dual tasking effect and thus lower stride time variability. In secondary analyses, we also examined the effects of ADHD and MPH on gait speed and the average stride time.

Patients and methods

Participants

The study group consisted of 16 children aged 9–16 years, who were diagnosed in an ADHD clinic as suffering from ADHD according to DSM IV diagnostic criteria [25]. Participants were not selected on the basis of subtype. Eleven participants met DSM-IV criteria for the inattentive subtype, and five participants met criteria for the combined hyperactive-impulsive/inattentive subtype. Diagnosis was made following a complete neuro-developmental evaluation by an experienced pediatric neurology team, including a pediatric neurologist with more than 10 years of experience treating ADHD (Y.L.) and a senior neuropsychologist in the Pediatric Neurology Unit at the Tel-Aviv Sourasky Medical Center. The diagnoses were made at least 1 year prior to the study, based on interviews with the parents, teachers, and children as well as by clinical examination and Conners' parent and teacher questionnaires [31, 32]. All subjects underwent a complete neuro-developmental evaluation as part of the initial assessment at the clinic and were found not to suffer from any major neurological or motor disability other than ADHD. Based on chart review and history, ADHD children were invited to participate only if they did not report or carry a formal diagnosis of any other (even minor) learning disabilities, neurological,

orthopedic, or psychiatric diagnoses according to DSM-IV criteria. ADHD children were invited to participate only if they were taking methylphenidate (Ritalin®, Novartis Pharmaceuticals Corporation) on a daily basis for at least a month prior to the study. Dosing was optimized for each ADHD participant (typically, 5–10 mg of short-acting methylphenidate), as per standard clinical practice, and each participant exhibited good clinical response to the medication. The participants were not treated with any other medication except MPH during the study period. Controls from the community were invited to participate if they met these exclusion criteria and were not diagnosed with ADHD. The control group consisted of 18 healthy children aged 7–17 years. Initially, self-report by the child and a parent was used to ensure that control subjects did not suffer from any symptoms suggestive of ADHD, or other neurological or cognitive disability. Subsequently, a pediatric neurologist examined the control subjects to confirm their normal neurological status. Both ADHD participants and controls were enrolled in age-appropriate grades in mainstream schools, suggesting a similar level of academic aptitude among the groups. Institutional Review Board approval was obtained for the study, and informed written consent was obtained.

Study design

ADHD subjects completed the study protocol on three occasions: (1) off medication, at least 72 hours after routine MPH was temporarily discontinued. (2) after taking their routine dose of MPH, and (3) after taking a placebo. On the second and third occasion, the child was given MPH or placebo, in a double blinded, randomized fashion, two hours before he/she participated in the study. The placebo pill was identical in appearance to the MPH pill. Thus, on average, subjects tested in the MPH condition had the same experience and exposure to previous tests as those tested in the placebo condition (i.e., half the subjects were tested off medications, then after taking MPH, and finally after taking the placebo, while for the other half of the subjects, the order was off medications, placebo, and then MPH). The control participants were studied once (without any medication).

Assessment of gait under usual and dual task conditions

Subjects were instructed to walk at their normal pace on level ground in a 150 meter-long hallway, for 4 minutes under each of two conditions: usual walking and a dual tasking condition. During the dual task condition, subjects listened to a text on tape while wearing a walkman-like device and earphones, using a previously established protocol [3, 7]. The specific text was chosen by the team psychologists to ensure age-appropriateness. In each text, a key word was chosen. This word was repeated several times in the text and relevant to its contents. Before the text was played, the child was informed about the specific word and he or she was then asked to keep track of how many times it appeared and to report the number of occurrences at the end of the walk. In addition, subjects were told to listen to the contents of the text and that they would be questioned about it after the walk. Following the walk, four questions were asked about the content of the text. The instructions for the dual task condition were to walk at a comfortable pace and to perform the secondary task. No specific instructions for priority of one of the tasks (walking vs. cognitive task) were given. Each subject performed the "dual task" in a seated position (with a different text on tape) before being asked to perform this task while walking. Previous studies have shown that this is a relatively mild dual task that can be characterized as a multi-task of passive listening and that it reduces gait speed in healthy young adults, in healthy older adults, in elderly fallers and in patients with Parkinson's disease, and also increases variability of gait timing in fallers and patients with Parkinson's disease [3, 7].

Gait was assessed using footswitches that enable the measurement of gait timing. Previously established methods [3, 6, 7, 33] were used to quantify gait speed, stride time, and the variability of stride time (using the coefficient of variation, CV). Subjects were asked to walk at their usual pace. Stride time variability quantifies the rhythmicity and automaticity of the gait pattern; higher CV values reflect decreased rhythmicity and reduced automaticity and have been shown to be associated with fall risk in adults [3, 9, 12].

Statistical analysis

Descriptive statistics are reported as mean ± SD. We used the Student's *t* and Chi-square tests to compare the ADHD and control subjects with respect to different background characteristics (e.g., age, gender). In order to estimate the effect of MPH and dual tasking on gait, we applied mixed effect models for repeated measures to evaluate within group and between group differences. The model does not assume equal variance between the ADHD and control groups. For each of the three gait measures, we applied a separate model where the dependent variable was the gait measure (a continuous one) and the independent variables were categorical: the group (ADHD, controls), the secondary task (none, dual tasking), and, for the ADHD group, medication status (none, placebo, MPH). The fixed factors in these models were group, the secondary task and the medication state, while the subject was the random factor. In each model, for the secondary task, the "none" category was considered as the reference category, inherent in the modeling procedure. P-values reported are based on two-sided comparisons. A p-value ≤ 0.05 was considered statistically significant.

Results

ADHD (off medication) vs. Controls

The characteristics of the study and control groups are summarized in Table 1. The two groups were similar with respect to age, gender, height, weight and years of education ($p \geq 0.26$). Table 2 compares the gait of the control group to the study group in the baseline condition (with the ADHD children tested 72 hours off MPH). At baseline (i.e., off MPH), gait speed and the average stride time were similar in the two groups. At baseline, stride time variability tended to be higher in the ADHD group compared to the control group ($p = 0.09$).

Dual tasking caused a significant reduction in gait speed in both groups (Table 2). Dual tasking tended to prolong the average stride time in both groups, consistent with the slowing of gait, however, these changes in the average stride time did not reach the level of significance in either group. Dual tasking caused a significant *decrease* in stride time variability in the ADHD group (opposite to the anticipated effect), while only a very small trend was observed in the control group.

Effects of MPH on the gait of children with ADHD

Table 3 summarizes the effects of MPH on the gait of the ADHD group. MPH did not have a significant effect on the average stride time during usual walking or during dual tasking. MPH tended to increase gait speed both during usual walking and during dual tasking (see Table 3). While both on and off MPH, there was a significant reduction in gait speed during dual tasking, compared to the single task condition (similar to that observed in the controls, recall Table 2). Compared to baseline (off MPH), MPH treatment significantly reduced usual walking stride time variability (see, for example, Fig. 1). In contrast to the off-MPH state, after taking MPH, dual tasking no longer significantly affected stride time variability (see Table 3).

Effects of placebo on the gait of children with ADHD

In general, gait measures during the placebo condition were not significantly different from the baseline, unmedicated state. The only measure that was significantly different from baseline was the average stride time during usual walking. There was a small, but significant increase in the average stride time in this condition. For stride time variability and gait speed, the values measured during the placebo condition were similar to the baseline condition, both during usual walking and during dual tasking ($p > 0.09$). Of note, as was the case for the unmedicated state, in the placebo condition, stride time variability was significantly lower during dual tasking as compared to usual walking ($p = 0.014$).

Performance on the secondary, cognitive tasks

Control subjects tended to perform better on the secondary, cognitive tasks, but group averages were not significantly different at baseline (off MPH). This was true both for the count of the number of keyword occurrences (% correctly counted during sitting: ADHD: 75.1 ± 24.1%; Controls: 87.2 ± 14.6%; $p = 0.23$) and the questions regarding the content (ADHD: 75.0 ± 20.4%; Controls: 91.7 ± 14.9%; $p = 0.18$). Performance on both tests tended to decline during dual tasking (i.e., during walking), for both groups, but the effects were not significant in either group (e.g., % correctly counted words during dual tasking: ADHD: 66.6 ± 28.8%; Controls: 78.6 ± 18.9%; $p = 0.23$). The placebo did not significantly affect performance on these tasks ($p > 0.47$). After taking MPH, listening comprehension did not improve ($p > 0.19$), both during sitting (62.5 ± 34.5%) and during walking (66.7 ± .28.9%). In the ADHD group, performance on the counting of the frequency of the appearance of certain words during sitting was not significantly different in response to MPH, but dual tasking performance significantly improved (to 86.9 ± 12.7%; $p = 0.005$), compared to baseline values.

Table 1 Demographics of the two groups*

	ADHD (n=16)	Controls (n=18)	P-Value
Age (yrs)	11.9 ± 1.8	12.5 ± 2.1	0.37
% girls	22%	19%	0.68
Height (cm)	151 ± 12	152 ± 13	0.81
Weight (kg)	43.4 ± 14.2	47.6 ± 17.4	0.44
Education (yrs)	5.8 ± 1.7	6.6 ± 2.4	0.26

*Values are mean ± SD or %, as indicated

The number of correct answers on the content of the story while sitting was associated with usual walking gait speed in the control subjects (Pearson's $r = -0.47$; $p = 0.051$) and with usual walking stride time variability in those with ADHD (Pearson's $r = 0.56$; $p = -0.031$). Gait speed also tended to be associated with word count performance (Pearson's $r = -0.46$; $p = 0.052$), but stride time variability was not ($p > 0.45$). Significant associations between performance on the secondary tasks and gait were not observed during dual tasking off medication. Although changes in gait speed and average stride time were not associated with changes in performance on the secondary, dual tasks in response to MPH ($p > 0.50$), the reduction in stride time variability during dual tasking in response to MPH was correlated with improvements in listening comprehension during dual tasking in response to MPH (Pearson's $r = 0.71$; $p = 0.023$). There was a similar trend for change in word count performance and stride time variability, but this was not statistically significant.

Discussion

Key findings

As noted in the Introduction, in this study of children with ADHD, we tested three hypotheses. The results support the first, to a degree, and the third hypothesis, but suggest that the second hypothesis should be rejected. Key findings of the present study include: (1) Gait speed and the average stride time are similar in children with ADHD and controls, while stride time variability tends to be increased in ADHD in the off-medication state. (2) Unexpectedly and in contrast to our second hypothesis, at baseline (off MPH), dual tasking significantly *decreased* stride time variability and enhanced automaticity in ADHD. (3) MPH sig-

Table 2 Gait in the control group and the ADHD group in the baseline condition in the two attention loading (dual tasking) conditions

	Attention Loading Condition	ADHD	Control	P-Value (group comparisons)
Average Stride Time (sec)	Usual Walking	1.04 ± 0.10	1.07 ± 0.11	0.36
	Dual Tasking	1.06 ± 0.10	1.09 ± 0.13	0.39
	P-Value (within group)	0.059	0.055	
Stride Time Variability (%)	Usual Walking	3.36 ± 1.18	2.81 ± 0.88	0.09
	Dual Tasking	2.75 ± 0.82	2.53 ± 0.80	0.49
	P-Value (within group)	0.004	0.11	
Gait Speed (m/sec)	Usual Walking	1.23 ± 0.19	1.23 ± 0.21	0.96
	Dual Tasking	1.17 ± 0.17	1.16 ± 0.21	0.84
	P-Value (within group)	0.007	0.001	

Table 3 The effects of attention loading (dual tasking) condition and methylphenidate (MPH) on gait in the children with ADHD

	Attention Loading Condition	No Medication	MPH	P-value (MPH vs. no med)
Average Stride Time (sec)	Usual Walking	1.04 ± 0.10	1.02 ± 0.08	0.56
	Dual Tasking	1.06 ± 0.10	1.03 ± 0.07	0.13
	P-value (loading effect)	0.059	0.32	
Stride Time Variability (%)	Usual Walking	3.36 ± 1.18	2.64 ± 0.94	0.001
	Dual Tasking	2.75 ± 0.82	2.41 ± 0.85	0.14
	P-value (loading effect)	0.004	0.24	
Gait Speed (m/sec)	Usual Walking	1.23 ± 0.19	1.27 ± 0.18	0.08
	Dual Tasking	1.17 ± 0.17	1.21 ± 0.15	0.08
	P-value (loading effect)	0.007	0.018	

nificantly decreased stride time variability and enhanced the automaticity and consistency of gait in ADHD (in support of the third hypothesis). (4) While MPH and dual tasking had similar effects on the variability of gait, they tended to have opposite effects on gait speed (MPH increased gait speed, but dual tasking caused a slowing down). (5) Both groups walked significantly slower during the dual tasking condition. Taken together, these findings indicate that even in children, gait is apparently influenced by attention (e.g., dual tasking affected gait in both groups) and that MPH enhances certain aspects of gait in ADHD.

Potential mechanisms

To our knowledge, this study is the first to quantitatively investigate the gait of ADHD children. Average stride time, gait speed and, by inference, stride length are not different compared to age-matched controls. On the other hand, ADHD subjects tend to have a less rhythmic and less automatic gait under usual walking conditions, compared to age-matched controls. This finding is consistent with previous reports that describe reduced motor-sensory synchronization as well as a deficit in paced sensory-motor abilities and in speeded motor tasks in ADHD children [34–36]. Reduced automaticity and increased stride time variability are also important features of the gait of patients with Parkinson's disease [7, 12, 37, 38], where dopamine deficits in the basal ganglia play a central role. Indeed, levodopa significantly improves stride time variability in patients with Parkinson's disease [12]. Perhaps the impaired dopamine uptake in ADHD contributes to the altered gait rhythmicity in ADHD. Conversely, MPH enhances the function of dopamine networks, improving rhythmicity, similar to that way that it potentiates dopamine uptake and modifies gait in Parkinson's disease [39]. Thus, one possibility is that the observed effect of MPH on gait was achieved via augmentation of what is classically referred to as "motor control."

Another, complementary explanation for the reduced gait automaticity in ADHD is possible. Studies in older adults suggest that the regulation of gait rhythmicity is a complex motor task that requires attention [3, 6, 7, 40]. If gait is "automatic" and does not require attention, dual tasking should not affect it. Yet many studies report the effects of dual tasking on locomotion [1, 3, 6, 7, 40–42]. Moreover, even among relatively healthy older adults, stride time variability is associated with executive function and attention abilities, while a simpler, more automatic and less complex motor task (e.g., finger tapping) is not [40]. The lower attentional capacities in ADHD may, therefore, contribute to the alteration in the rhythmicity of gait.

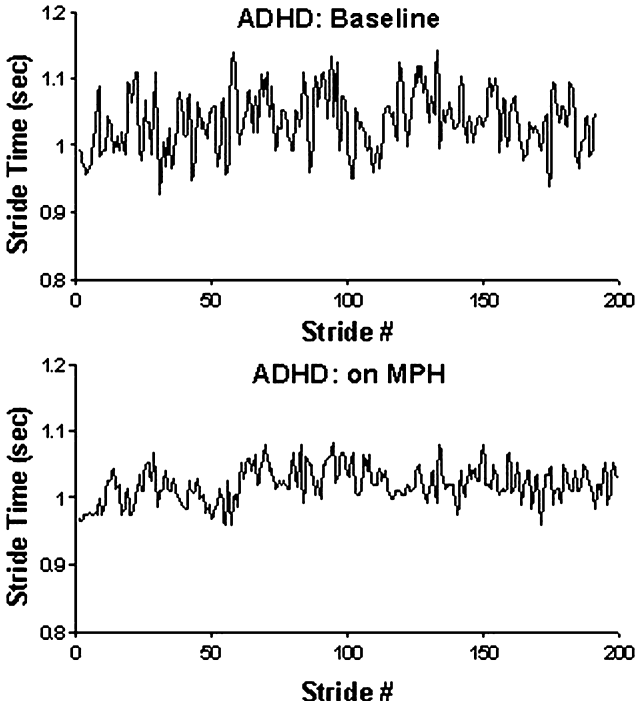

Fig. 1 Example of the effects of methylphenidate (MPH) on stride time variability during usual walking in a child with ADHD. Above: baseline (72 hours off MPH). Below: after treatment with MPH. Note how the stride-to-stride fluctuations are reduced in response to MPH

This view is supported by the observation that MPH improved rhythmicity in the present study. It is well-documented that attention and executive function are impaired in ADHD [24–29, 43] and that MPH improves executive function and attention in ADHD [19–23, 26], in part due to its action on dopamine networks, especially in the frontal and prefrontal cortex, an area of the brain that is largely responsible for executive function (e.g., dual tasking) and attention [44]. Indeed, previous work has shown that MPH augments frontal activation [44, 45]. According to this explanation, the enhanced attention that comes about as a result of MPH leads to an improved gait rhythmicity. In support of this idea, we note that MPH improved the gait rhythmicity of patients with Parkinson's disease while it did not affect a more simple motor task, i.e., finger tapping abilities [46]. Further, in the present study, MPH did not affect finger tapping (mean rate or variability, data not shown). Similarly, other investigations reported deficits in executive function in ADHD, despite intact finger tapping performance [47, 48]. Moreover, despite the known deficits in executive function, attention and the abilities of subjects with ADHD to perform dual tasks, accuracy on a drawing task was not affected by a dual task [49], suggesting that not all motor tasks are influenced by attention in ADHD. These findings are consistent with the idea that MPH enhances attention and that this, in turn, improves gait automaticity, an attention demanding task.

Of course, in addition to its attention-enhancing effects, MPH also may impact other systems that directly or indirectly influence gait including catecholamine regulation in locomotor control networks and in the brainstem and spinal cord. Similarly, MPH may also affect behavior and other aspects of cognitive function such as hyperactivity and impulsivity, common symptoms of ADHD. It is possible that changes to these symptoms may have also contributed to the observed increase in gait automaticity and rhytmicity.

A priori, another possible reason for the observed effects of MPH relates to the order of the testing. By design, MPH testing always occurred after the off medication, baseline condition. One could argue that practice, learning of the task, and/or familiarity with the setup produced the reduced stride time variability during the MPH condition. The results from the placebo condition, which were equivalent to the MPH condition with respect to practice, learning, and familiarity, suggest that this is not a likely explanation. MPH brought about a significant reduction in the usual walking stride time variability, whereas the placebo did not. Older adults and patients with Parkinson's disease who were tested multiple times over several weeks also demonstrated that placebo, learning and/or practice does not influence repeated measures of variability [50, 51]. Thus, it seems likely that MPH, but not practice or any placebo effect, was responsible for the observed reduction in stride time variability in the MPH condition.

Effects of dual tasking

The effects of attention loading are somewhat unexpected. The ADHD group responded to an attention loading task by walking more slowly. Previous work using other dual task paradigms indicates that, in general, the dual task effects of middle school children are for the most part similar to those of adults [52, 53]. It is, therefore, not surprising that the dual tasking effect on gait speed is similar to the response observed in other populations. However, the ADHD subjects walked *more* rhythmically during the dual tasking condition, compared to the single task, usual walking condition. This response is different from what has been reported in both healthy adults and in older adult patients. In those populations, dual tasking either has no effect or it decreases rhythmicity [3, 6, 7, 33]. Perhaps the improved rhythmicity under dual tasking in the ADHD group could be explained by a higher attentional level (vigilance) created by presenting them with a cognitive challenge. Another possible explana-

tion is that the additional cognitive load required under dual task conditions creates an "automatic pilot" control of gait. This is consistent with the constrained action hypothesis, according to which an external focus promotes the use of more automatic control processes [54]. For example, studies have shown that adaptation of an external focus may improve the performance of motor tasks such as postural control, biceps curls and basketball free throws [54–56]. Zachry et al. [56] suggested that, "an external focus of attention enhances movement economy, and presumably reduces 'noise' in the motor system that hampers fine movement control and makes the outcome of the movement less reliable". This theory could explain the significant reduction in stride variability during dual tasking in the ADHD group. While there was a similar tendency in the control subjects, the effect of dual tasking on stride time variability was not significant so that, in essence, the overall response of the control group was similar to that observed in healthy adults (i.e., decreased gait speed with no significant effect on stride time variability).

Regardless of the precise explanation, the effect of MPH on dual tasking can be viewed as reducing the dual tasking effect on motor performance. With MPH, dual tasking no longer altered stride time variability, so that just as in the controls, now there were no significant effects of dual tasking on this aspect of gait. The association between changes in the performance on the secondary, dual task and the change in stride time variability in response to MPH supports the idea that enhanced attention abilities contributed to the reduced dual task effect on gait seen when subjects were tested on MPH. Previous investigations using other dual tasks have also reported that MPH reduces the decrement associated with tasks that require executive function and the splitting of attention in children with ADHD [22, 57]. Cepeda et al. suggested that the MPH effect on executive function is what produces the improvement in task-switching performance. As noted above, this could also largely account for the effects of MPH in the present study of a sustained attention, dual task, but other mechanisms may have also played a role (e.g., effects on dopamine and catecholamines). The lack of a significant correlation between change in word count performance (another measure of attention and the "dual task" performance) and change in stride time variability in response to MPH may be due to the confounding effect of these other mechanisms, the sample size, and the possibility that this relationship was not linear. Another interpretation of the observed findings is that that the reduction in stride time variability in response to MPH in the dual tasking condition may be due to a reduced distraction from other stimuli as much as to an increase in attention abilities per se. Finally, it is possible that MPH and dual tasking are independent effects that act on stride variability in the same direction.

Limitations and potential clinical ramifications

A more complete explanation is needed to account for the unanticipated reaction to dual tasking in children with ADHD and why it differs from that seen in age-matched controls, healthy adults, and other adult patient populations. Future studies should also further investigate the influence of MPH on motor speed and quality of movement in both normal adults and children as well as in those suffering from movement disorders, motor disabilities and developmental disorders. Larger scale studies including those that evaluate the possible confounding effects of innate cognitive abilities and IQ, those that investigate differences among the various subtypes of ADHD, and those that examine the response to different levels and types of distractions and dual tasks may also be informative. In addition, it would be interesting to see whether there is any connection between the not fully explained high injury rate in children with ADHD [30] and the observed reduced gait automaticity, a measure that has been related to fall risk in other populations. Be that is it may, the present findings demonstrate, for the first time, that ADHD may affect gait.

The present findings also provide evidence linking gait rhythmicity and automaticity to attention. MPH, a drug whose main effect is the enhancement of attention, apparently reinforces gait automaticity and minimizes the dual tasking effect in ADHD. This supports the idea that the regulation of gait should be viewed as a complex, cognitively demanding motor task [40]. Moreover, it suggests the possibility that improvement of cognitive function may help to stabilize the gait of patients who walk with an inconsistent and irregular gait pattern and a high risk of falls. A recent open-label pilot study of the effects of MPH in patients with Parkinson's disease found results similar to the present study and strengthens this concept [46]. Nonetheless, it remains to be determined how the present findings extend to other motor tasks and to other clinical populations and whether cognitive function therapeutics can be used to enhance gait and improve locomotor function in patient groups who suffer from more significant impairment of gait automaticity and altered cognitive function (e.g., Alzheimer's disease, Parkinson's disease, elderly fallers).

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References

1. Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16:1–14
2. Shkuratova N, Morris ME, Huxham F (2004) Effects of age on balance control during walking. Arch Phys Med Rehabil 85:582–588
3. Springer S, Giladi N, Peretz C, Yogev G, Simon ES, Hausdorff JM (2006) Dual-tasking effects on gait variability: the role of aging, falls, and executive function. Mov Disord 21:950–957
4. Camicioli R, Howieson D, Lehman S, Kaye J (1997) Talking while walking: the effect of a dual task in aging and Alzheimer's disease. Neurology 48:955–958
5. Lundin-Olsson L, Nyberg L, Gustafson Y (1997) "Stops walking when talking" as a predictor of falls in elderly people. Lancet 349:617
6. Sheridan PL, Solomont J, Kowall N, Hausdorff JM (2003) Influence of executive function on locomotor function: divided attention increases gait variability in Alzheimer's disease. J Am Geriatr Soc 51:1633–1637
7. Yogev G, Giladi N, Peretz C, Springer S, Simon ES, Hausdorff JM (2005) Dual tasking, gait rhythmicity, and Parkinson's disease: Which aspects of gait are attention demanding? Eur J Neurosci 22:1248–1256
8. Hausdorff JM (2005) Gait variability: methods, modeling and meaning. J NeuroEng Rehabil 2:doi:10.1186/1743-0003-2-19
9. Hausdorff JM, Rios D, Edelberg HK (2001) Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 82:1050–1056
10. Herman T, Giladi N, Gurevich T, Hausdorff JM (2005) Gait instability and fractal dynamics of older adults with a "cautious" gait: why do certain older adults walk fearfully? Gait Posture 21:178–185
11. Nakamura T, Meguro K, Sasaki H (1996) Relationship between falls and stride length variability in senile dementia of the Alzheimer type. Gerontology 42:108–113
12. Schaafsma JD, Giladi N, Balash Y, Bartels AL, Gurevich T, Hausdorff JM (2003) Gait dynamics in Parkinson's disease: relationship to Parkinsonian features, falls and response to levodopa. J Neurol Sci 212:47–53
13. Bloem BR, Hausdorff JM, Visser JE, Giladi N (2004) Falls and freezing of gait in Parkinson's disease: a review of two interconnected, episodic phenomena. Mov Disord 19:871–884
14. Buchner DM, Larson EB (1987) Falls and fractures in patients with Alzheimer-type dementia. JAMA 257:1492–1495
15. Bradley JD, Golden CJ (2001) Biological contributions to the presentation and understanding of attention-deficit/hyperactivity disorder: a review. Clin Psychol Rev 21:907–929
16. Levy F (1991) The dopamine theory of attention deficit hyperactivity disorder (ADHD). Aust N Z J Psychiatry 25:277–283
17. Silk T, Vance A, Rinehart N, Egan G, O'boyle M, Bradshaw JL, Cunnington R (2005) Fronto-parietal activation in attention-deficit hyperactivity disorder, combined type: functional magnetic resonance imaging study. Br J Psychiatry 187:282–283
18. Zametkin AJ, Liotta W (1998) The neurobiology of attention-deficit/hyperactivity disorder. J Clin Psychiatry 59(Suppl 7):17–23
19. Wilens TE, Spencer TJ, Biederman J (2002) A review of the pharmacotherapy of adults with attention-deficit/hyperactivity disorder. J Atten Disord 5:189–202
20. Homer CJ, Baltz RD, Hickson GB, Miles PV, Newman TB, Shook JE, Zurhellen WM, Lowe BA, Schwalenstocker E, Goldberg MJ, Shiffman R, Berger JE, France FL, Perrin JM, Stein MT, Amler RW, Blondis TA, Feldman HM, Meyer BP, Shaywitz BA, Wolraich ML, DeSpirito A, Homer CJ, Pierce K, Ganiats TG, Grabert B, Brown RT (2000) Clinical practice guideline: Treatment of the child with attention-deficit/hyperactivity disorder. Pediatrics 108:1033–1044
21. Jensen PS, Arnold LE, Severe JB, Vitiello B, Hoagwood K (2004) National Institute of Mental Health Multimodal Treatment Study of ADHD follow-up: 24-month outcomes of treatment strategies for attention-deficit/hyperactivity disorder. Pediatrics 113:754–761
22. Kramer AF, Cepeda NJ, Cepeda ML (2001) Methylphenidate effects on task-switching performance in attention-deficit/hyperactivity disorder. J Am Acad Child Adolesc Psychiatry 40:1277–1284
23. Rapport MD, Moffitt C (2002) Attention deficit/hyperactivity disorder and methylphenidate. A review of height/weight, cardiovascular, and somatic complaint side effects. Clin Psychol Rev 22:1107–1131
24. Gillberg C (2003) Deficits in attention, motor control, and perception: a brief review. Arch Dis Child 88:904–910
25. Homer CJ, Baltz RD, Hickson GB, Miles PV, Newman TB, Shook JE, Zurhellen WM, Lowe BA, Schwalenstocker E, Goldberg MJ, Shiffman R, Berger JE, France FL, Perrin JM, Stein MT, Amler RW, Blondis TA, Feldman HM, Meyer BP, Shaywitz BA, Wolraich ML, DeSpirito A, Homer CJ, Pierce K, Ganiats TG, Grabert B, Brown RT (2000) Clinical practice guideline: Diagnosis and evaluation of the child with attention-deficit/hyperactivity disorder. Pediatrics 105:1158–1170
26. Langleben DD, Monterosso J, Elman I, Ash B, Krikorian G, Austin G (2006) Effect of methylphenidate on Stroop Color-Word task performance in children with attention deficit hyperactivity disorder. Psychiatry Research 141:315–320
27. Steger J, Imhof K, Coutts E, Gundelfinger R, Steinhausen HC, Brandeis D (2001) Attentional and neuromotor deficits in ADHD. Dev Med Child Neurol 43:172–179
28. Wilding J (2005) Is attention impaired in ADHD? British Journal of Developmental Psychology 23:487–505
29. Willcutt EG, Doyle AE, Nigg JT, Faraone SV, Pennington BF (2005) Validity of the executive function theory of attention-deficit/hyperactivity disorder: A meta-analytic review. Biological Psychiatry 57:1336–1346
30. Pastor PN, Reuben CA (2006) Identified attention-deficit/hyperactivity disorder and medically attended, nonfatal injuries: US school-age children, 1997–2002. Ambul Pediatr 6:38–44
31. Conners CK, Sitarenios G, Parker JD, Epstein JN (1998) Revision and restandardization of the Conners Teacher Rating Scale (CTRS-R): factor structure, reliability, and criterion validity. J Abnorm Child Psychol 26:279–291
32. Conners CK, Sitarenios G, Parker JD, Epstein JN (1998) The revised Conners' Parent Rating Scale (CPRS-R): factor structure, reliability, and criterion validity. J Abnorm Child Psychol 26:257–268
33. Costa M, Peng CK, Goldberger AL, Hausdorff JM (2003) Multiscale entropy analysis of human gait dynamics. Physica A-Stat Mech Appl 330:53–60

34. Ben Pazi H, Gross-Tsur V, Bergman H, Shalev RS (2003) Abnormal rhythmic motor response in children with attention-deficit-hyperactivity disorder. Dev Med Child Neurol 45:743–745
35. Blondis TA (1999) Motor disorders and attention-deficit/hyperactivity disorder. Pediatr Clin North Am 46:899–vii
36. Pitcher TM, Piek JP, Hay DA (2003) Fine and gross motor ability in males with ADHD. Dev Med Child Neurol 45:525–535
37. Hausdorff JM, Cudkowicz ME, Firtion R, Wei JY, Goldberger AL (1998) Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntington's disease. Mov Disord 13:428–437
38. Morris ME, Iansek R, Matyas TA, Summers JJ (1996) Stride length regulation in Parkinson's disease. Normalization strategies and underlying mechanisms. Brain 119 (Pt 2):551–568
39. Nutt JG, Carter JH, Sexton GJ (2004) The dopamine transporter: importance in Parkinson's disease. Ann Neurol 55:766–773
40. Hausdorff JM, Yogev G, Springer S, Simon ES, Giladi N (2005) Walking is more like catching than tapping: gait in the elderly as a complex cognitive task. Exp Brain Res
41. Bloem BR, Valkenburg VV, Slabbekoorn M, Willemsen MD (2001) The Multiple Tasks Test: development and normal strategies. Gait Posture 14:191–202
42. Verghese J, Buschke H, Viola L, Katz M, Hall C, Kuslansky G, Lipton R (2002) Validity of divided attention tasks in predicting falls in older individuals: a preliminary study. J Am Geriatr Soc 50:1572–1576
43. Fuggetta GP (2006) Impairment of executive functions in boys with attention deficit/hyperactivity disorder. Child Neuropsychol 12:1–21
44. Nieoullon A (2002) Dopamine and the regulation of cognition and attention. Prog Neurobiol 67:53–83
45. Vaidya CJ, Austin G, Kirkorian G, Ridlehuber HW, Desmond JE, Glover GH, Gabrieli JD (1998) Selective effects of methylphenidate in attention deficit hyperactivity disorder: a functional magnetic resonance study. Proc Natl Acad Sci USA 95:14494–14499
46. Auriel E, Hausdorff JM, Herman T, Simon ES, Giladi N (2006) Effects of methylphenidate on cognitive function and gait in patients with Parkinson's disease: a pilot study. Clin Neuropharmacol 29:15–17
47. Bayliss DM, Roodenrys S (2000) Executive processing and attention deficit hyperactivity disorder: an application of the supervisory attentional system. Dev Neuropsychol 17:161–180
48. Sami N, Carte ET, Hinshaw SP, Zupan BA (2003) Performance of girls with ADHD and comparison girls on the Rey-Osterrieth Complex Figure: evidence for executive processing deficits. Neuropsychol Dev Cogn C Child Neuropsychol 9:237–254
49. Miyahara M, Piek J, Barrett N (2006) Accuracy of drawing in a dual-task and resistance-to-distraction study: motor or attention deficit? Hum Mov Sci 25:100–109
50. Hausdorff JM, Nelson ME, Kaliton D, Layne JE, Bernstein MJ, Nuernberger A, Singh MA (2001) Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise. J Appl Physiol 90:2117–2129
51. Lowenthal J (2004) The effect of rhythmic auditory stimulation upon gait dynamics in Parkinson's disease. Tel-Aviv University
52. Dossett D, Burns B (2000) The development of children's knowledge of attention and resource allocation in single and dual tasks. J Genet Psychol 161:216–234
53. Irwin-Chase H, Burns B (2000) Developmental changes in children's abilities to share and allocate attention in a dual task. J Exp Child Psychol 77:61–85
54. Wulf G, McNevin N, Shea CH (2001) The automaticity of complex motor skill learning as a function of attentional focus. Q J Exp Psychol A 54:1143–1154
55. Wulf G, Prinz W (2001) Directing attention to movement effects enhances learning: a review. Psychon Bull Rev 8:648–660
56. Zachry T, Wulf G, Mercer J, Bezodis N (2005) Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. Brain Res Bull 67:304–309
57. Cepeda NJ, Cepeda ML, Kramer AF (2000) Task switching and attention deficit hyperactivity disorder. J Abnorm Child Psychol 28:213–226