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Cognitive performance is improved while walking: Differences in cognitive–sensorimotor couplings between children and young adults

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We investigated how 9-year-olds and young adults performed a working memory task under different difficulty conditions while walking on a treadmill. Stride-length and stride-time variability tended to decrease with cognitive load in young adults, whereas children showed an increase in walking variability when cognitive load was very high. Participants in both age groups improved their cognitive performance when walking at their preferred speed as opposed to sitting or walking at a fixed, non-preferred speed. We conclude that the interaction of walking and cognitive performance is influenced by sharing resources between two tasks, and that performance improvements in cognition may be caused by an exercise-induced activation of resources.

Keywords: Children; Dual-task performance; Gait variability; Physiological arousal; Resource competition; Young adults.

INTRODUCTION

Dual-task situations, namely the simultaneous execution of two tasks, are common in everyday life. Examples are reading the newspaper while having breakfast or going for a walk while being engaged in a lively conversation

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with a friend. Often, one of the two tasks is a sensorimotor task (e.g., walking or keeping one's balance on a bus), and the other task is a cognitive task (e.g., trying to remember which groceries have to be bought on the way home). Research concerning people's ability to perform two tasks concurrently has referred to these types of situations as dual-task or multi-task situations, and resource theories have often been used to explain the resulting behaviour. The underlying assumption is that attentional resources are limited and have to be shared between the two tasks (Kahneman, 1973; Wickens, 1991). Therefore, when the demands of the two tasks exceed the individual's processing resources, performance decrements are to be expected, which are often referred to as dual-task costs. Note that this line of reasoning assumes that the two tasks compete for the same pool of limited resources. However, assuming that there might be multiple resource pools instead, and that the amount of specific resources required for performing certain tasks depends on the task characteristics of the two component tasks, allows for the explanation of a larger variety of potential findings in the dual-task research domain (Navon & Gopher, 1979). Under the assumption of multiple resource pools, the execution of two concurrent tasks only suffers if some of the resources required to perform one of the tasks are also necessary to perform the other task.

Concerning age differences in the ability to perform two tasks concurrently, children have often been reported to show larger performance decrements in a dual-task situation than young adults (see Guttentag, 1989, for a review). This pattern has been replicated in studies with cognitive–sensorimotor dual-tasks (see Huang & Mercer, 2001, for a review), and such situations have also often led to higher performance decrements in older as opposed to younger adults (see Schaefer, Huxhold, & Lindenberger, 2006, for a review). For example, Krampe, Schaefer, Lindenberger, and Baltes (2008) had 9- and 11-year-olds and young adults walk on a narrow track while concurrently performing a semantic word-fluency task. Participants from all three age groups reduced their walking speed to a comparable extent when performing the word-fluency task, but only 9-year-olds additionally showed reductions in their word-fluency performance, while 11-year-olds and young adults were able to maintain their cognitive performance under dual-task conditions.

Not every cognitive–sensorimotor dual-task study, however, shows higher overall dual-task costs in children as compared to young adults. Schaefer, Krampe, Lindenberger, and Baltes (2008) conducted a study in which 9- and 11-year-olds and young adults were balancing on an ankle-disc board while concurrently performing either an episodic memory task or a working memory task. Task difficulties of the cognitive tasks had been adjusted individually to each participant's performance level. Under dual-task conditions, cognitive performance was reduced in all age groups, but only adults showed more body sway on the ankle-disc board as compared to the single-task condition. Children, on the other hand, reduced their body sway under dual-task conditions, and therefore showed smaller dual-task-related performance decrements when dual-task costs were aggregated over the two task domains. This pattern of performance was interpreted as an incidence of adaptive resource allocation in the children's groups, since children were operating closer to their stability boundaries already under single-task conditions and protected their body's equilibrium under dual-task conditions by further reducing their body sway.

In general, resource theories (no matter whether they assume a general resource or a pool of independent resources) assume that performing two tasks concurrently will either lead to no changes in performance or to performance decrements. However, there might be situations in which performance is even improved in a dual-task situation. These cases have usually not been interpreted within the dual-task research framework, but have been explained in terms of an increase in "arousal" or "activation", which may be caused by performing a sensorimotor task (e.g., exercising on a bicycle ergometer) that leads to increases in physical arousal (Kahneman, 1973). This increase in arousal or activation, then, has beneficial consequences for the performance of the secondary cognitive task, at least as long as the exercise intensity is not approaching the individual's maximum capacity.

McMorris and Graydon (2000) reviewed several such studies. According to their review, increments in speed of cognition with exercise were observed in several studies, and performance was sometimes further improved when participants were exercising with maximum intensity, especially when the cognitive task was rather complex. However, accuracy of cognitive performance—as opposed to speed—has generally not been improved significantly by incremental exercise. It is therefore assumed that individuals are able to allocate resources to task-relevant information, even during maximal exercise. McMorris and Graydon further mentioned methodological concerns that questioned the validity of several of the studies, namely the fact that exercise protocols usually did not take individual differences in fitness levels into account, and that cognitive tasks differed considerably in complexity and familiarity.

Other studies not included in the overview article by McMorris and Graydon (2000) further support the assumption of cognitive performance enhancements with exercise (Adam, Teeken, Ypelaar, Verstappen, & Paas, 1997; Collardeau et al., 2001). For example, Collardeau et al. (2001) conducted a study in which trained triathletes were running on a treadmill at a velocity that corresponded to their ventilatory threshold. In the testing session, five 10 minute submaximal treadmill runs were separated by four over-ground runs (10 minutes each). Before, during, and after running on the treadmill, the athletes performed a simple reaction time task. Reaction times were slowed compared to the pre-test performance in the first treadmill run only. After that run, a significant effect of exercise duration on simple reaction time was observed, with significantly faster reaction times after 40 minutes of exercise and thereafter. This effect is unlikely to have been caused exclusively by a practice effect, since pre- and post-test reaction times that were recorded at rest did not differ significantly. The authors suggested that simple cognitive performance can be improved during exercise, despite the negative effect of dual-tasking, and they assumed that the underlying reason for this improvement was an increase in arousal induced by a prolonged exercise.

In addition, it has been investigated whether there are age differences between children of different ages and young adults in the ability to profit from an exercise-induced arousal. Deakin et al. (1988) had 8-year-olds, 11-year-olds, and young adults perform a visual detection task at rest and while walking at 75% of their maximum heart rate. Over and above the main effect of age group, with 8-year-olds' visual detection being inferior to 11-year-olds' and young adults' performance, responses were quicker at all levels of distraction when targets were present while participants were exercising. This effect was most apparent when many distracting items were presented in the display, and it did not interact with age. This indicates that children are also able to profit from exercise and can improve their cognitive performance due to exercise-induced arousal.

The current study investigated whether walking on a treadmill at either a fixed or a self-chosen speed while concurrently performing a cognitive task (N-back working memory task) with different levels of task difficulty would lead to decreases or increases in cognitive performance as compared to a baseline condition in which the cognitive task was performed while sitting on a chair. We also investigated whether 9-year-olds and young adults differed in these dual-task performance patterns. A previous study using the same experimental paradigm in young and older adults indicated that cognitive performance did not change between single- and dual-task conditions when participants were walking at their self-chosen speed (Lövdén, Schaefer, Pohlmeyer, & Lindenberger, 2008). Decreases in performance would be predicted by a resource account that assumes that the two tasks compete for limited resources, while performance increases would be predicted if one assumes that sensorimotor performance leads to an increase in arousal or activation, which then can be invested into the cognitive task. Concerning age differences, a resource account would predict that children have fewer resources available than young adults, so that their dual-task-related performance decrements are greater than those observed in young adults. Under the assumption that cognitive performance profits from an increase in arousal or activation associated with the sensorimotor task, it is an open question whether this effect should be more pronounced in children or young adults.

Li, Krampe, and Bondar (2005) discussed four methodological concerns that should be taken into account when conducting cognitive–sensorimotor dual-task research (see also Lindenberger, Marsiske, & Baltes, 2000). They argued that the tasks that are used should mimic everyday processing demands in multi-tasking. We tried to incorporate this concern in the current study by having participants walk on a treadmill while being engaged in a working memory task. We used the N-back task, which taps central cognitive functions, like the monitoring, short-term storage, and scheduled retrieval of the presented stimuli, and which also involves executive control processes (Dobbs & Rule, 1989). Second, Li et al. argued that co-ordination costs should be calculated for all tasks involved. Since we measured cognitive performance as well as several gait parameters such as stride time and stride length, we were able to investigate dual-task-related changes in both task domains. The third methodological concern states that task difficulties should be varied systematically to challenge individuals' potentials at an age-appropriate level. We included a difficulty manipulation of the two tasks in our design (i.e., performance on the N-back was assessed at four different difficulty levels, and walking on the treadmill was performed at a fixed speed of 2.5 km/h and at a self-chosen speed). Finally, Li and colleagues argued that differential-emphasis manipulations should be used, in which participants are instructed to exert control over their resource allocation operations, by shifting their attention more to one task than to the other. We refrained from taking this consideration into account, since it is unclear whether shifting one's attention to the performance of a rather automatized task such as walking has detrimental or beneficial consequences for task performance (Huxhold, Li, Schmiedek, & Lindenberger, 2006).

METHOD

Participants

Thirty-two 9-year-olds ($M_{age} = 9.0$ years; $SD_{age} = 0.18$ years; 16 girls and 16 boys) and 32 younger adults ($M_{age} = 25.3$ years; $SD_{age} = 2.89$ years; 16 women and 16 men) were sampled from the participant pool of the Max Planck Institute for Human Development, Berlin, Germany. Exclusion criteria for young adults were diagnosed disorders directly affecting gait and balance, diabetes and diagnosed heart problems. Children with orthopaedic disorders, balance problems (e.g., acute or chronic ear infections), meningitis, attention-deficit-hyperactivity syndrome (ADHS) or with neurological disorders (e.g., cerebral palsy, brain tumours, epilepsy) were excluded. All participants had normal or corrected-to-normal vision and hearing. Parts of the data from the group of young adults have been previously reported by Lövdén et al. (2008) as comparison data for a sample of older adults.

Perceptual speed (Digit-Symbol Substitution; Wechsler, 1981) and vocabulary (MWT-A; Lehrl, Merz, Burkard, & Fischer, 1991) were assessed to document cognitive age typicality of the sample. For the item-per-second score of the Digit-Symbol Substitution Test, a t-test revealed that young adults scored significantly more items per second than 9-year-olds, $t(39.87) = 15.2$, $p < .001$. Furthermore, young adults had significantly higher scores than 9-year-olds on the vocabulary test, as indicated by a t-test for independent samples with $t(61) = 10.0$, $p < .001$. The overall picture on these cognitive measures is consistent with the developmental literature showing that cognitive speed and knowledge of vocabulary improve during development (e.g., Case, Kurland, & Goldberg, 1982; Fry & Hale, 1996).

Participants provided written consent prior to the experiment and received €50 for their participation. Parents provided written consent for their children. The study was approved by the ethics committee of the Max Planck Institute for Human Development.

Apparatus

A 12-camera (infrared V-cam 100 & 200) Vicon motion capture system (Vicon 612, Workstation 4.6; Vicon Ltd, Oxford, UK), sampling at 200 Hz, was used for capturing participants' motion on the treadmill. Gym shoes in all sizes were prepared with reflector markers at the big toes and the heels, and an additional 35 reflector markers were attached to participants' bodies for the motion analyses.

Participants walked on a treadmill (Woodway GmbH, Weil am Rhein, Germany) which had its walking area (200×70 cm) at the level of the surrounding floor. No handrail was present. In order to prevent complete falls, a safety harness was fastened around the waist of the participant and to the ceiling.

A 200×270 cm screen was mounted in front of the treadmill. A virtual environment consisting of a straight path was back projected to the screen (175×234 cm). The visual flow of the virtual environment was synchronized to the speed of the treadmill with an empirically established flow/speed ratio (see also Lövdén, Schellenbach, Grossmann-Hutter, Krüger, & Lindenberger, 2005). The reason for projecting the virtual environment was to reduce the risk that participants unnaturally focused on the experimental environment while avoiding fixation at one point in space.

Design and procedure

The experimental design for the cognitive measures was a 2 (Age Group: children/young adults) × 2 (Setting: sitting/walking) × 2 (Walking Speed: fixed speed/preferred speed) × 4 (WM Load: 1-back to 4-back) factors design. For the sensorimotor variables, the design was a 2 (Age Group: children/young adults) × 2 (Walking Speed: fixed speed/preferred speed) × 5 (WM Load: no load to 1-back to 4-back) factors design. The sensorimotor variables of interest in the current study were the coefficient of variation for stride time and stride length. The coefficient of variation (CV) is the standard deviation divided by the mean—CV = (standard deviation/mean) × 100—and it is often used in cases when variances of distributions with different means are compared, and when mean value and variance are dependent on each other (Beauchet, Dubost, Herrmann, & Kressig, 2005; Ebersbach, Dimitrijevic, & Poewe, 1995). Stride length is defined as the distance covered in two steps, which is from one heel strike to the next heel strike of the same foot. Accordingly, stride time is defined as the time to perform one stride. Stride-to-stride fluctuations in walking are assumed to be a sensitive marker for gait control and gait stability, with higher variability representing a less consistent and less stable walking pattern (Hausdorff, 2005).

Data collection consisted of two sessions. One session involved walking at a fixed speed (2.5 km/h) and one involved walking at a preferred speed. The order of sessions was counterbalanced. Anthropometric data (e.g., height, weight) was obtained in the beginning of the first session. Cognitive ability measures were assessed at the beginning of the second session. Participants were tested individually in sessions that lasted approximately two hours.

In each session, participants were given at least seven minutes to become familiar with the treadmill. Different walking velocities were introduced. In the "preferred speed" condition, the participant selected a tempo allowing natural and rhythmic walking with which they felt comfortable. Otherwise the fixed speed was introduced for at least three minutes. The participants completed the four conditions of the single-task N-back (1-, 2-, 3-, and 4-back) while sitting comfortably on a chair. Next, the single-task walking (no load condition) was carried out, during which the motion capture started 30 seconds after the participants had started walking on the treadmill. Motion capture lasted for about 20 seconds. Then the participant walked and performed the N-back task simultaneously (dual-task condition). Depending on the counterbalancing condition, the dual-task phase started with N-back 1 or N-back 4. Each N-back task was repeated twice. The auditory N-back started 30 seconds after the participant had started walking on the treadmill. Motion capture started 39 seconds after the auditory N-back had started and lasted for about 21 seconds. Between the first and second trial there was an interval of 30 seconds. The subject did not stop walking on the treadmill during that time. Finally, the second trial of single-task N-back 4, 3, 2, and 1 was performed while sitting on a chair.

The N-back tasks involved series of 26 digits from 1 to 9 presented via loudspeakers. Depending on the condition of WM load, participants verbally responded with "yes" whenever a digit was heard that was the same as the one presented 1, 2, 3, or 4 positions back in the series. All responses were noted by the experimenter and later scored as correct or false alarms. Six "yes" responses were required in each trial for perfect performance, so the maximum score was 6 points for each trial. One point was subtracted from the score for each false alarm. The inter-stimulus interval varied randomly between 2350 and 3150 milliseconds to prevent rhythmical influences on gait. To minimize articulation during the motion capture, none of the six target items occurred in the 20-second interval in which motion was captured (item 13–item 21).

Data processing and statistical analyses

The motion data (heel and toe markers) were post-processed in MATLAB 6.5 (Mathworks, Sherborn, MA). From the 20 seconds of motion data from each trial, the first and last 2.5 seconds were discarded due to unreliable data. From the remaining 15 seconds, 9 gait cycles were extracted for all individuals. Mean and coefficient of variation for stride time and stride length over the 18 steps were computed separately for the left and right foot and the two trials of each condition. Subsequently, the estimates for left and right foot were averaged. A few ($<3\%$) outliers ($\pm$ 3 *SD*s) were replaced by the values of the other trial in a condition before averaging across the two trials of each condition.

Mixed ANOVAs were performed separately for the dependent variables. For the sensorimotor variables, a 2 (Age Group: younger/older) $\times$ 2 (Walking Speed: preferred/fixed) $\times$ 5 (Task: no load–4-back) ANOVA addressed the effects of walking with no load as compared to walking under different difficulty levels of the cognitive task and the influence of walking speed. WM load and task were within-subject factors. For WM performance, a 2 (Age Group: younger/older) $\times$ 2 (Walking Speed: preferred/fixed) $\times$ 2 (Setting: sitting/walking) $\times$ 4 (WM Load: 1-back to 4-back) ANOVA was performed. WM load, walking speed, and setting were within-subject factors. For within-subject effects, the multivariate *F*-values are reported. In cases in which variances were not equal in *t*-tests or in which the sphericity assumption was not met in mixed-design ANOVAs, corrected degrees of freedom have been used. The alpha level was .05.

RESULTS

Walking behaviour

Young adults preferred a faster walking velocity ($M = 3.73$ km/h, $SD = 0.39$) than 9-year-old children ($M = 3.09$ km/h, $SD = 0.41$), $t(61.86) = 6.4$, $p < .001$. In addition, the self-selected walking velocity of both 9-year-old children and young adults was significantly faster than the given fixed-speed velocity of 2.5 km/h. Concerning age differences in mean values of gait parameters, children showed shorter stride lengths, higher cadences, and briefer stride times than young adults in both speed conditions. This pattern has often been reported in the literature (Adolph, Vereijken, & Shrout, 2003; Hausdorff, Zemany, Peng, & Goldberger, 1999). Since participants in the current study were not able to change their walking speed during a trial due to the constant speed of the treadmill, analyses of gait parameters will focus on the variability of stride time and stride length. Stride-to-stride variability is considered to be a sensitive marker for gait control, and gait instability is characterized by increased variability from one stride to the next (Hausdorff, 2005).

Figures 1 and 2 depict the results for stride time and stride length as function of working-memory load under preferred and fixed-speed conditions. An inspection of these figures suggests that young adults tend to decrease the variability of their gait with increasing cognitive load,

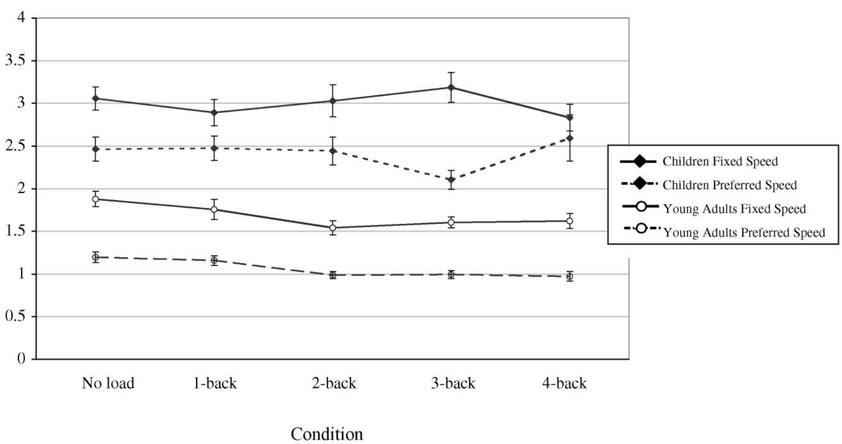

Figure 1. Age differences in the influence of cognitive load on stride time variability as measured by the coefficient of variation (CV). Children's stride time variability is depicted by squares, and young adults' stride time variability is depicted by circles. Solid lines represent performance in the fixed-speed condition, and dashed lines represent performance in the preferred-speed condition. Error bars depict standard errors of the mean.

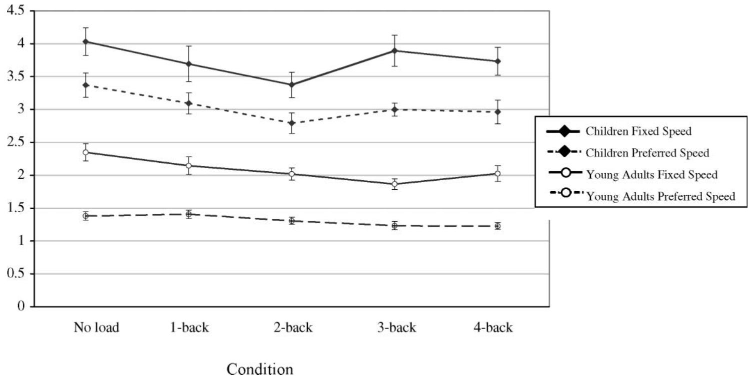

Figure 2. Age differences in the influence of cognitive load on stride length variability as measured by the coefficient of variation (CV). Children's stride time variability is depicted by squares, and young adults' stride time variability is depicted by circles. Solid lines represent performance in the fixed-speed condition, and dashed lines represent performance in the preferred-speed condition. Error bars depict standard errors of the mean.

especially in the preferred-speed condition, while the pattern is less consistent for children, who sometimes tend to show a rather U-shaped function, with increases in gait variability when cognitive load is very high.

In order to address this pattern of data statistically, a mixed-design ANOVA with Cognitive Load (5: no load, N-back 1 to 4) and Speed (2: preferred speed vs. fixed speed) as within-subjects factors and Age Group (2) as between-subjects factor was conducted for stride time and stride length. Since preliminary analyses showed no main effect for sex in the current study, this factor was not considered.

A significant effect for age group was detected for stride time, $F(1,\ 60) = 128.9$, $p < .001$, $\eta^2 = .68$, and stride length, $F(1,\ 60) = 159.2$, $p < .001$, $\eta^2 = .73$. Children showed a higher variability in those gait parameters as compared to young adults, a pattern that has often been reported in the literature (Hausdorff et al., 1999; Stolze et al., 1997; Sutherland, 1997).

A significant Cognitive Load effect was detected for stride length, $F(3.43,\ 206.03) = 11.5$, $p < .001$, $\eta^2 = .16$, but this effect was qualified by an interaction of Cognitive Load and Age Group, $F(3.43,\ 206.03) = 5.4$, $p = .001$, $\eta^2 = .16$, with children showing more pronounced differences between the load conditions than young adults. These effects were not present for stride time.

A main effect for the factor Speed was found for stride time, $F(1,\ 60) = 79.6$, $p < .001$, $\eta^2 = .57$, and stride length, $F(1,\ 60) = 50.1$, $p < .001$, $\eta^2 = .46$. Participants showed a higher variability in those gait parameters under fixed-speed conditions as compared to preferred-speed conditions, which might have been caused by a decrease in postural stability at lower speeds (Shumway-Cook & Woollacott, 2001). The main effect of Speed did not interact with Age Group for any gait parameter. For stride time, a significant interaction of Cognitive Load and Speed, $F(2.77, 166.22) = 3.1$, $p < .05$, $\eta^2 = .05$, and also an interaction of Cognitive Load, Speed and Age Group, $F(2.77, 166.22) = 3.4$, $p < .05$, $\eta^2 = .05$, were detected.

To follow-up these significant interactions involving walking speed and task condition, separate analyses were conducted for the preferred- and fixed-speed conditions in children and young adults. To address non-linear trends we inspected the orthogonal polynomial contrasts. Results showed a significant linear trend in the preferred-speed condition for stride time, $F(1, 31) = 30.6$, $p < .001$, $\eta^2 = .50$, and stride length, $F(1, 31) = 10.7$, $p < .01$, $\eta^2 = .26$, in the young adults, and the quadratic trend reached significance for stride length in children, $F(1, 29) = 6.4$, $p < .05$, $\eta^2 = .18$. For the fixed-speed condition, the pattern was less consistent, with both the linear and the quadratic trend reaching significance for stride time and stride length in the young adults, linear trend for stride time: $F(1, 31) = 10.8$, $p < .01$, $\eta^2 = .26$; quadratic trend for stride time: $F(1, 31) = 5.8$, $p < .05$, $\eta^2 = .16$; linear trend for stride length: $F(1, 31) = 6.2$, $p < .05$, $\eta^2 = .17$; quadratic trend for stride length: $F(1, 31) = 6.3$, $p < .05$, $\eta^2 = .17$, and only the quadratic trend for stride length reaching significance in the children's sample, $F(1, 31) = 6.3$, $p < .05$, $\eta^2 = .17$.

In sum, variability of stride time and stride length was higher in children than in young adults, and it was higher under fixed-speed conditions than preferred-speed conditions. Moreover, young adults tended to decrease their gait variability as a function of cognitive load, whereas children decreased their gait variability when working on an easy cognitive task (1-back and 2-back), but increased the variability again when cognitive load was very high (3-back and 4-back). However, the pattern was not consistent across all walking velocities and for both gait parameters.

Cognition

In order to investigate performance changes in the cognitive task, an overall mixed-design ANOVA with Cognitive Load Condition (4: N-back 1 to 4), Task Condition (2: single-task vs. dual-task), and Speed (2: preferred vs. fixed speed) as within-subjects factors, and Age Group (2) as between-subjects factor was conducted. Preliminary analyses showed no main effect of sex, and this factor was not included in the analyses. In addition, analysing only the rate of false alarms per trial indicated that it was generally low, with less than one false alarm per trial even in the most difficult condition for the children's group.

A significant difference between the performances in different Cognitive Load Conditions was detected, $F(1.52, 92.64) = 392.0$, $p < .001$, $\eta^2 = .87$, and that effect interacted with Age Group, $F(1.52, 92.64) = 32.6$, $p < .001$, $\eta^2 = .35$. Cognitive performance decreased with increasing cognitive load, and that effect was more pronounced in the children's group.

Furthermore, the within-subjects factor Task Condition (single- vs. dual-task) reached significance, $F(1, 61) = 9.3$, $p < .01$, $\eta^2 = .13$, and that effect did not interact with Age Group. Participants improved their cognitive performance under dual-task conditions.

No main effect for the within-subjects factor Speed (preferred vs. fixed speed) was detected, but the interaction of Speed and Task Condition (single- vs. dual-task) reached significance, $F(1, 61) = 9.4$, $p < .01$, $\eta^2 = .13$, indicating that cognitive improvement was more pronounced in the preferred-speed condition than in the fixed-speed condition.

In addition, the two age groups differed significantly in their performance in the working memory task, $F(1, 61) = 63.7$, $p < .001$, $\eta^2 = .51$, with young adults outperforming children.

To further follow-up the significant interaction of walking speed and task condition, separate analyses were conducted for the preferred- and fixed-speed conditions. Figures 3 and 4 depict the performance patterns graphically. Figure 3 presents the performance in the preferred-speed condition, and Figure 4 in the fixed-speed condition. In the fixed-speed condition, both 9-year-old children and young adults maintained their cognitive performance under dual-task conditions in comparison to single-task conditions. In the preferred-speed condition, both age groups significantly increased their cognitive performance under dual-task conditions, $F(1, 61) = 21.7$, $p < .001$, $\eta^2 = .26$, and this effect interacted with age group, $F(1, 61) = 6.8$, $p < .05$, $\eta^2 = .10$, indicating that children benefited to a greater extent from the dual-task situation than young adults. Moreover, the interaction of Task Condition (single- vs. dual-task) and Cognitive Load reached significance, $F(1.962, 119.664) = 3.4$, $p < .05$, $\eta^2 = .05$. With increasing cognitive load, a more pronounced increase in N-back working memory performance was found under dual-task conditions, probably because participants were performing at ceiling in the N-back 1 condition and therefore could not further improve their performance in a dual-task situation.[1] However, as can be seen in Figures 3 and 4, single-task performances tended to be slightly higher in children for the preferred-speed condition as compared to the fixed-speed condition. We therefore calculated

[1]If the data of the N-back 1 condition were excluded from all the analyses of cognitive performances, the same pattern of findings emerged, with just one exception: In the analysis of the preferred-speed condition, the interaction of Task Condition (single vs. dual task) and Cognitive Load did not reach significance ($p = .334$).

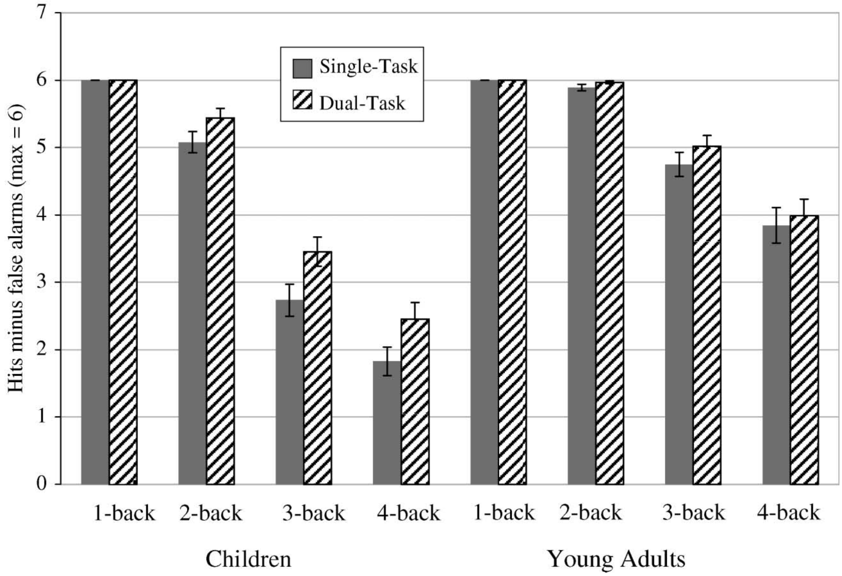

Figure 3. Cognitive performance when sitting and when walking with preferred speed. Single-task performance is presented by the solid bars, and the corresponding dual-task performance is presented by the striped bars. Error bars depict standard errors of the mean.

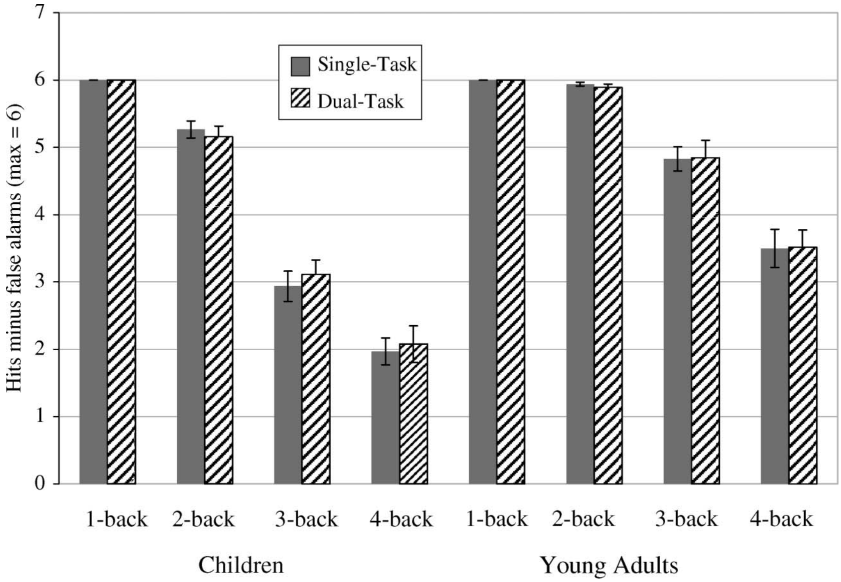

Figure 4. Cognitive performance when sitting and when walking with fixed speed (2.5 km/h). Single-task performance is presented by the solid bars, and the corresponding dual-task performance is presented by the striped bars. Error bars depict standard errors of the mean.

an average single-task score for both sessions for each individual, and re-ran the ANOVAs reported above. There were no differences in the results for fixed speed, but the interaction effect of single- vs. dual-task and age group did not reach significance any more for the ANOVA with preferred speed. In other words, when averaging the single-task scores for both sessions, children and young adults benefited to a comparable extent from walking on the treadmill.

DISCUSSION

This study explored differences between children's and young adults' ability to perform more or less challenging cognitive tasks while walking. Concerning gait variability, the study revealed that variability of stride time and stride length was higher in 9-year-olds than in young adults, and it was higher under fixed-speed conditions as compared to preferred-speed conditions. Furthermore, with increases in cognitive load, young adults tended to decrease their gait variability, whereas children showed a tendency to decrease their gait variability when working on an easy cognitive task (N-back 1 and 2), but to increase the variability again when cognitive load was very high (N-back 3 and 4). However, the pattern was not consistent across all walking velocities and the two gait parameters. Nevertheless, there are similarities to the findings of Huxhold and colleagues (2006), who reported a decrease in postural sway under conditions in which participants were focusing their attention on an easy cognitive task, as compared to focusing their attention exclusively on the execution of the automatized sensorimotor task of balancing. When the difficulty of the cognitive task was further increased, older, but not younger, adults showed an increase in postural sway, indicating that there is a U-shaped relation between the efficacy of postural control and concurrent cognitive demands. Children in the current study might be comparable to older adults in the study by Huxhold and colleagues (2006), since they had fewer resources available than young adults, and therefore might have begun to increase their gait variability with a nominally smaller cognitive load than young adults (see also Lövdén et al., 2008). An alternative explanation for the reduction in walking variability from no load to the dual-task conditions with low cognitive load might be that participants are always engaged in some kind of cognitive activity (e.g., mind wandering) under single-task walking conditions, which might be cognitively more demanding than performing the easy cognitive task while walking (Fraizer & Mitra, 2008). From this perspective, any "single-task" performance of a rather automatized sensorimotor task includes an unspecified cognitive task of unknown load.

Concerning performance in the working-memory task, young adults outperformed children. In addition, performance decreased in all age groups when cognitive load was increased, and this effect was more pronounced in 9-year-old children than in young adults. The manipulation of task difficulty in the cognitive task guaranteed that performance was well below ceiling in the most challenging task conditions. Both age groups significantly improved their cognitive performance when walking on the treadmill at their preferred speed as opposed to sitting on a chair. This effect was more pronounced in the higher cognitive load conditions. It is unlikely that the improvement in cognitive performance from single- to dual-task conditions was due to a practice effect, since (a) single-task trials were assessed at the beginning and end of each session (ABBA-scheme) and (b) there were no performance differences between single- and dual-task conditions in the fixed-speed condition.

The data pattern of the current study therefore lends empirical support to theoretical assumptions that predict an increase in arousal or activation associated with physical activity (Adam et al., 1997; Collardeau et al., 2001; Deakin et al., 1988), which then can be invested into the cognitive task.[2] However, performance improvements only occurred in the preferred-speed condition, in which participants were able to choose a comfortable walking speed, and they did not occur when participants were asked to walk at a fixed, non-preferred speed of 2.5 km/h.

There are two possible explanations for why cognitive performance was not improved in the fixed-speed condition: Walking at the fixed speed, which was considerably slower than the preferred speed in both age groups, might simply not have been fast enough to increase arousal sufficiently to achieve an effect. Given that most studies that investigated the effect of exercise-induced arousal increases had participants perform at rather fast speeds (see McMorris & Graydon, 2000, for a review), usually while exercising on a bicycle ergometer or while running on a treadmill, ensuring that they were performing at a certain percentage of their maximum exercise capacity (VO_{2max}), the movement required in the current study (walking on a treadmill) was definitely physically less demanding. Since we did not measure exercise-induced physical arousal directly (e.g., increases in heart rate or oxygen consumption during walking as opposed to sitting), we are not able to report at which stage participants were performing relative to their maximum capacity.

[2]In comparison to other studies that report no changes in accuracy of task performance, but a decrease in reaction times to cognitive tasks with increasing physical activity (Collardeau, Brisswalter, & Audiffren, 2001; Deakin, Starkes, & Elliott, 1988), the current study only focused on increases in accuracy. Potential changes in reaction times from single- to dual-task conditions have not been measured, since task instructions focused exclusively on accuracy, and not on reaction times.

Alternatively, and following a dual-task resource competition approach (Kahneman, 1973; Wickens, 1991), which assumes that resources have to be shared between the two tasks, it is conceivable that walking on a treadmill at a fixed, non-preferred speed is more resource demanding than walking at one's preferred speed, since one has to pay some attention to adjusting one's walking speed to the speed of the treadmill. Studies on the automatization of sensorimotor skills (Beilock, Carr, MacMahon, & Starkes, 2002a; Beilock, Wierenga, & Carr, 2002b) indicate that automatized sensorimotor skills require very little or no attention for their execution, and that paying attention to the execution of an automatized skill leads to performance decrements. If adjusting one's walking speed to the fixed speed of the treadmill, one might have to refrain from using the speed that is most comfortable and therefore also most automatized, and if the constant adaptation of one's speed to the fixed speed of the treadmill is resource demanding, no resources might have been left for investing in the improvement of cognitive performance.

In order to distinguish between the two accounts, future studies should include a third walking velocity in the study design, in which people are instructed to walk faster, rather than slower, than their preferred speed. The arousal-induced resource activation account would predict that this should lead to further improvements in cognitive performance (at least as long as the exercise intensity is not extremely high), while the resource competition account would predict that any walking velocity that differs from one's preferred walking speed should require attentional resources and therefore lead to a reduction in cognitive performance. In this respect, it would also be interesting to use some other motor task, for example cycling on a stationary bicycle, which leads to an increase in arousal while presumably requiring less cognitive resources than walking on a treadmill. In order to distinguish between the two accounts, some objective measure of arousal (e.g., galvanic skin response or heart rate) should also be included in future studies.

A design limitation of the current study is that the time period in which the motion capture took place (and in which no target stimuli were presented for the N-back task) was implemented at the same point in time across trials, and it might therefore have become predictable for subjects. However, we consider it rather unlikely that this might have led to participants temporarily "giving up" working on the N-back task. In order to exclude that possibility in future studies, the timing of the silent motion capture period should be varied randomly across trials.

Another important extension of the reported results would be to include special populations (e.g., patients with cerebral palsy, orthopaedic problems influencing gait patterns, or dyslexia) in cognitive–sensorimotor dual-task studies. It is conceivable that those groups show a more pronounced pattern of dual-task-related performance decrements than healthy individuals, even when taking each individual's single-task performance into account. An interesting population in this respect are individuals suffering from attention-deficit hyperactivity disorder (ADHD). Motor restlessness is one symptom of this disorder. Since the current study demonstrated that healthy children were able to improve their cognitive performance when walking on a treadmill at comfortable speed, hyperactive children might also be able to profit from some type of consistent movement that does not require much attention, even though it is often argued that those children have more problems than healthy controls when they have to divide their attention between two concurrent tasks (Fuggetta, 2006; Wimmer, Mayringer, & Raberger, 1999). On the other hand, exercise is reported to have positive effects on cognitive performance and overall behaviour in ADHD children (Azrin, Ehle, & Beaumont, 2006; Baker, 2005; Tantillo, Kesick, Hynd, & Dishman, 2002; Wendt, 2000), but no study has, to our knowledge, investigated the influence of concurrent motor activity on cognitive performance in that group.

To conclude, stride-to-stride variability decreased with cognitive load in young adults, whereas children showed an increase in variability when cognitive load was very high. Both children and adults improved their cognitive performance when walking at their preferred speed as opposed to sitting or walking at a fixed, non-preferred speed. This improvement was more pronounced in children than in young adults. Thus, the interaction of walking and cognitive performance is influenced by the necessity to share resources between the tasks, and improvements in cognitive performance can be induced by exercise through the activation of resources. Future studies need to identify the brain mechanisms underlying arousal-induced resource activation.

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