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Age-related changes in children's cognitive–motor dual tasking: Evidence from a large cross-sectional sample

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ABSTRACT

Children coordinate two tasks simultaneously at several occasions throughout the day; however, this dual-task ability and its development across childhood are poorly understood. Therefore, the current study investigated age-related changes in children's dual-task ability using a large cross-sectional sample of 8- to 13-year-old children ($N = 135$). In our dual-task methodology, children were asked to walk across an electronic pathway while performing three concurrent cognitive tasks. These tasks targeted at children's executive function components: inhibition, switching, and updating skills. Our findings indicate associations between age and children's stride time variability but not with normalized velocity. Younger children showed higher stride time variability in the dual-task situation as compared with older children after accounting for their single-task performance, intelligence, anthropometric variables, and sex, indicating a more regular gait pattern in older children. Furthermore, age was differently related to children's accuracy in solving the concurrent cognitive tasks. Whereas age was associated with children's performance in the updating and switching task, there was no relation between age and children's inhibitory skills. In addition, our data imply that children's dual-task ability was associated with a number of individual variables. In particular, children with higher intelligence scores showed fewer errors and girls showed lower stride time variability in the dual tasks. Our results suggest a considerable developmental

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progression in children's ability to coordinate two simultaneous tasks across middle childhood. Furthermore, our study qualifies previous dual-task research and implies that heterogeneous findings may be related to a differential involvement of executive function components in the dual task.

Introduction

The ability to coordinate two tasks increases our efficiency in daily life. There are multiple situations in which we perform two tasks simultaneously such as when we talk to a friend while walking through town. Combining several concurrent tasks is a typical behavior in adults' and children's lives. However, even though we are continuously performing two tasks simultaneously, this dual-task ability and its development across childhood and adolescence are less well understood. The current study aimed to add evidence to this topic and investigated age-related changes in children's dual-task ability in a large sample of typically developing children aged 8 to 13 years. To this end, we used a prototypical cognitive–motor dual task and asked children to walk while solving several concurrent cognitive tasks (Hagmann-von Arx, Manicolo, Lemola, & Grob, 2016; Hocking et al., 2020). Importantly, and in contrast to several previous studies, the current study implemented methodological shortcomings identified in previous research (Saxena, Cinar, Majnemer, & Gagnon, 2017), which allowed considerably extending those recent studies.

On several situations throughout the day, children walk while performing a concurrent cognitive task. Whereas children's cognitive skills are typically assumed to follow a protracted development across childhood and adolescence (e.g., Kail, 1991), children's motor development is often associated with the developmental phase of infancy (Adolph, Tamis-Lemonda, & Karasik, 2010). Indeed, walking shows the most dramatic changes during the first 6 months after walking onset (Adolph, Vereijken, & Shrout, 2003; Bril & Ledept, 1998; Hallemans, De Clercq, & Aerts, 2006). However, there are gait parameters such as velocity and gait variability that continue to develop throughout childhood and do not reach an adult-like level until approximately 7 or 8 years of age (velocity: Bril & Ledept, 1998; Sutherland, 1997; Sutherland, Olshen, Cooper, & Woo, 1980) or even at mid-adolescence (gait variability: Hagmann-von Arx et al., 2016; Hausdorff, Zemany, Peng, & Goldberger, 1999). Furthermore, children show considerable development with respect to planning and coordinating their walking behavior in order to meet external constraints (Gill, 2015). Therefore, it seems that human gait follows a rather protracted development, especially when focusing on fine-grained gait parameters (Diamond, 2000).

Previous research investigating walking in cognitive–motor dual tasking revealed that in particular higher-order cognitive skills such as executive functions seem to be important for keeping postural control in walking (for a meta-analysis, see Al-Yahya et al., 2011; for reviews, see Beurskens & Bock, 2012; Schaefer, 2014; Woollacott & Shumway-Cook, 2002; Yogev, Hausdorff, & Giladi, 2008). Executive functions are defined as higher-level cognitive processes that are used to "engage, direct, or coordinate other (lower) cognitive processes, typically in the service of goals" (Doebel, 2020, p. 942; see also Diamond, 2013; Miyake & Friedman, 2012). This conclusion was supported by a number of studies with children (e.g., Rabaglietti, De Lorenzo, & Brustio, 2019; Schott & Klotzbier, 2018) and older populations (e.g., Springer et al., 2006) and was further indicated by pronounced effects in clinical samples with deficits in executive functioning (e.g., Beerse, Henderson, Liang, Ajisafe, & Wu, 2019; Möhring, Klupp, & Grob, 2018; Yogev et al., 2005).

The demand of executive functions in walking was explained using dual-task theories such as the *capacity-sharing theory* (Kahneman, 1973; Wickens, 1991). According to this theory, walking and the concurrent cognitive task may compete for a limited amount of resources. Consequently, performance in one or both tasks is reduced in the dual task as compared with the single task (i.e., dual-task costs emerge). There are also other dual-task theories that predict interference effects but differ with respect to the source of this interference (e.g., the *bottleneck theory:* Pashler, 1994; the *cross-talk theory:* Navon & Miller, 1987). Whereas the majority of dual-task studies with children showed interference effects (for a review, see Ruffieux, Keller, Lauber, & Taube, 2015), the question of whether dual-task ability improves across childhood (i.e., dual-task costs decrease with age) remains insufficiently answered as of today. Some studies revealed evidence for an age-related progression (e.g., Krampe, Schaefer, Lindenberger, & Baltes, 2011; Sebastian & Hernández-Gil, 2016; for reviews, see Berger, Harbourne, & Horger, 2018; Guttentag, 1989), whereas another set of studies did not find any age-related changes (e.g., Anderson, Bucks, Bayliss, & Della Sala, 2011; Imbo & Vandierendonck, 2007; Irwin-Chase & Burns, 2000; for a review, see Saxena et al., 2017).

Even though comparing these studies is challenging given the fact that various age groups and tasks were involved, these contradicting findings may be explained by the methodological characteristics of some of these studies. A recent review summarized methodological considerations for dual-task assessments (Saxena et al., 2017), which help in evaluating dual-task studies. For example, several studies may have limited power to assess age-related differences because they have used rather small samples with wide age ranges (e.g., 20 participants aged 7–16 years in Boonyong, Siu, van Donkelaar, Chou, & Woollacott, 2012). Other studies have used only a small number of trials in the dual tasks, which may have lowered reliability of the relevant measures (e.g., Hagmann-von Arx et al., 2016; Hocking et al., 2020). Furthermore, some studies did not account for children's single-task performance (e.g., Lejeune, Desmottes, Catale, & Meulemans, 2015), which is crucial to quantify the extent of performance *change* from single-task to dual-task performance. Moreover, only few studies have equated single-task performance in one or both tasks to control for individual differences in the baseline condition (e.g., Anderson et al., 2011; Hocking et al., 2020; Krampe et al., 2011; Saxena, Majnemer, Li, Beauchamp, & Gagnon, 2019; Schaefer, Krampe, Lindenberger, & Baltes, 2008). This approach is important to disentangle age effects on children's single-task performance from potential age effects on their ability to *coordinate* the two tasks (Saxena et al., 2017; Somberg & Salthouse, 1982) and is crucial in light of interindividual differences in children's baseline performance.

The current study aimed to qualify previous research while taking care to address those methodological concerns. Based on the points outlined above, we (a) used a large cross-sectional sample of 8- to 13-year-old children, (b) applied a large number of trials for each task, (c) adjusted children's performance levels in the single tasks to a comparable level, and (d) accounted for interindividual differences in children's single-task performance in our analyses (in addition to other control variables). Moreover, given the importance of executive functions for walking (Woollacott & Shumway-Cook, 2002; Yogev et al., 2008), we included concurrent cognitive tasks that targeted children's executive functioning. Building on research showing that executive functions consist of three distinct but related components (Diamond, 2013; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; but see Doebel, 2020), children were presented with three tasks tapping their inhibition, switching, and updating skills while walking across an electronic pathway system (see also Möhring et al., 2020). This electronic mat allowed objectively capturing several gait parameters. Based on previous research showing age-related changes for gait velocity and stride time variability (Hagmann-von Arx et al., 2016; Hocking et al., 2020), we focused on these two gait parameters.

The goals of the current study were twofold. On a general level, we investigated age-related changes in children's dual-task ability after addressing several methodological criteria (Saxena et al., 2017). On a more specific level, we explored whether age relates differently to dual-task performance in the three executive function components considering their different developmental trajectories (Best & Miller, 2010). Previous research demonstrated that inhibitory control seemed to develop at an earlier age as compared with switching and updating, with some studies describing a peak at 5 to 8 years (Romine & Reynolds, 2005) and others at 10 to 12 years of age (Huizinga, Dolan, & van der Molen, 2006). By contrast, switching and updating seemed to follow a more protracted developmental trajectory, with an adult-like level being reached by mid-adolescence (Davidson, Amso, Anderson, & Diamond, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004; Luciana, Conklin, Hooper, & Yarger, 2005). In summary, for the first time, the current study investigated age-related changes in children's dual-task ability (at 8–13 years of age) in tasks combining walking with all three components of executive functions (as compared with their single-task performance).

Method

Participants

A sample of 8- to 13-year-old children (N = 135; for demographic details, refer to Table 1) participated in the current cross-sectional study.[1] An additional 3 participants were tested but excluded due to critical or missing test scores in the standardized tasks (n = 2) or technical problems (n = 1). Children were students from schools in the area of Basel, Switzerland, with the majority of participants being Caucasian. A subsample of participants (<20%) had a migration background; however, their level of language skills was fluent to ensure that they understood the task instructions. Exclusion criteria comprised a diagnosis of a developmental disorder (particularly a disorder affecting the executive functions or gait), an intellectual impairment (as indicated by an IQ < 70), and a suspected developmental coordination disorder (as indicated by a cutoff of less than the 16th percentile in our motor test battery) (Petermann, 2008). The current study was approved by the ethics committee in Basel, Switzerland and was performed in accordance with the rules laid down in the 1964 Declaration of Helsinki and its later amendments. Children provided verbal assent and parents gave written informed consent prior to participation. Children and their families received a voucher for their participation.

Measures

Participants were tested at a laboratory of the respective university. In the first test session, children's single-task performance in gait and executive functions and their cognitive–motor dual tasking was assessed. Prior to the single and dual tasks, we controlled for children's color vision using Ishihara plates (Ishihara, 1960) and measured their height, weight, leg length, and shoe size. In the second test session, children completed a number of standardized tests. For example, to assess children's intellectual functioning, they were examined with a short form of the Wechsler Intelligence Scale for Children–Fourth Edition (WISC-IV; Petermann & Petermann, 2011). Following recommendations from Waldmann (2008), children's IQ score was computed by testing the four subtests of vocabulary, matrix reasoning, letter–number sequencing, and coding. In addition, to assess their motor ability, children were tested using the Movement Assessment Battery for Children–Second Version (Henderson, Sugden, & Barnett, 2007; Petermann, 2008).

Walking assessment

Walking was measured objectively using a gait assessment system (GAITRite Platinum; CIR Systems, Sparta, NJ, USA) that was shown to be highly reliable and valid in measuring children's gait (Dusing & Thorpe, 2007). This 7.01-m-long electronic mat consists of 23,040 sensors. Effects of acceleration and deceleration were reduced by adding two identical but inactive sections (1.25 m) to the beginning and end of this mat (with participants not being aware of this inactivity). Participants started walking right before the first inactive section, walked across the sensitive part of the mat, and stopped walking after the last inactive part of the mat. In accordance with previous research (e.g., Hagmann-von Arx et al., 2016; Hocking et al., 2020), we accounted for participants' leg length by measuring their normalized velocity in single-task and dual-task situations. Furthermore, we assessed participants' stride-to-stride fluctuations with respect to temporal aspects (stride time), as expressed by the coefficient of variation (CV; Yogev et al., 2005)

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[1] Previous research showed a moderate effect size of f^2 = .15 (Hagmann-von Arx et al., 2016) investigating similar research questions. A priori power analyses with G*Power 3.1 based on this effect size, assuming a power of .80 and using a significance level of p < .05, revealed a minimum sample size of 118 individuals to detect age-related development in children's cognitive–motor dual tasking in a hierarchical regression (after accounting for anthropometric measures and intelligence and including different executive function tasks and interactions with age in the same model). Consequently, the current study can be seen as adequately powered.

Table 1
Children's demographic and anthropometric characteristics and children's means (and standard errors) of their motor and cognitive performance as well as their dual-task costs in each trial of the executive function task.

		Inhibition	Switching	Updating
Demographic and anthropometric characteristics				
Age (years)	10.667 (0.028)			
Gender (% female)	45.2			
Height (cm)	147.632 (0.206)			
Weight (kg)	38.900 (0.179)			
Performance level (%) after the adjustment phase		96.35 (0.29)	94.87 (0.71)	94.22 (1.47)
Motor and cognitive performance (per trial)				
Normalized velocity (ST, m/s)	1.527 (0.004)			
Normalized velocity (DT, m/s)		1.358 (0.007)	1.334 (0.007)	1.301 (0.007)
CV stride time (ST, %)	2.002 (0.016)			
CV stride time (DT, %)		2.297 (0.037)	2.367 (0.034)	2.500 (0.039)
Errors (ST, *n*)		0.546 (0.248)	1.272 (0.422)	1.338 (0.070)
Errors (DT, *n*)		0.462 (0.227)	1.237 (0.429)	1.351 (0.683)
Dual-task costs (proportional)				
Normalized velocity		.104 (.004)	.123 (.004)	.144 (.004)
CV stride time		.331 (.251)	.368 (.025)	.450 (.028)
Errors		.107 (.019)	.203 (.026)	.484 (.048)

Note. N = 135. ST, single task; DT, dual task; CV, coefficient of variation. Dual-task costs = (dual task − single task) / single task * ±1, with (−) multiplier for gait velocity that is expected to decrease in the dual-task situation and (+) multiplier for gait variability that is expected to increase in the dual-task situation (Saxena et al., 2019). Given that some participants showed no errors in the single task, it was impossible to calculate cognitive dual-task costs. Here, we followed common practice and added a constant to the original data (+1) in each executive function task in order to compute cognitive dual-task costs.

Assessment of executive functions

Inhibition. Children were presented with the animal Stroop task in which they saw pictures of animals (i.e., dolphin, chick, frog, and ladybug; refer to Fig. 1A) (Grob & Hagmann-von Arx, 2018). They were instructed to name the correct color of this animal (e.g., yellow when seeing the chick). The test phase consisted of 96 items, with half of them showing animals presented in black–white (*neutral* item type), 12 items showing correctly colored animals (*congruent* item type; e.g., a chick presented in yellow), and 36 items showing incorrectly colored animals (*incongruent* item type; e.g., a chick presented in blue). Item types were prerandomized in eight test trials with 12 items each. Accuracy served as the dependent variable.

Switching. Children were presented with the local–global task (Navon, 1977). They saw a large global figure consisting of many smaller local figures (e.g., a square consisting of smaller circles; see Fig. 1B). These figures consisted of circles, crosses, triangles, or squares that were combined systematically with the exception that the larger figure could not consist of the same smaller shapes (e.g., a large cross consisting of smaller crosses). Children were instructed to name the large global geometric figure when the figure was presented in blue, and they were instructed to name the small local figure when the figure was presented in black. Therefore, with colors changing from trial to trial, children needed to switch from the global features to the local features and vice versa. The test phase included 96 items, with approximately half of them involving a switch (from local to global features or vice versa) and the other half involving no switch (e.g., two black figures presented consecutively). Different item types were prerandomized in eight test trials with 12 items each. Accuracy served as the dependent variable.

Updating. Updating was measured with an *n*-back task (Dobbs & Rule, 1989). Children saw digits ranging from 1 to 9. These digits were presented randomly and sequentially with the exception that digits never appeared in their ordinal sequence (e.g., 1, 2, 3; 6, 5, 4). Children were instructed to remember and postpone the naming of each digit until the second-next digit was presented (2-back; Schaefer et al., 2008). The test phase consisted of 96 items that were prerandomized in eight test trials with 12 items each. Accuracy served as the dependent variable.

Procedure

Two experimenters coordinated the first experimental session, assessing children's cognitive–motor dual tasking. First, participants' single-task performance (baseline) was assessed for the cognitive domain. To this end, participants solved three executive function tasks—each tapping their inhibition, switching, or updating skills—while sitting in a chair. Children were asked to say their answer out loud. Stimuli were presented on a wall in front of the participants using a projector (distance: 3.20 m; projection area: 1.50 m high × 2.20 m wide). Stimuli had the following sizes: digits in updating (30 cm high × 15 cm wide); figures in switching (75 cm high × 65 cm wide); pictures of animals in inhibition (42–50 cm high × 33–54 cm wide, depending on the animal).

Every cognitive single task started with practice trials to familiarize participants with each executive function task. Then, participants' individual performance level was adjusted to a comparable 90% performance level in each executive function task (for a detailed description, see next section). After this adaptive phase, participants solved the first half of single-task trials (four trials) in each executive function task with individually adjusted difficulty levels while sitting in a chair. Immediately afterward, participants' motor single-task performance was assessed. To this end, participants were asked to walk eight times across the electronic pathway system without a concurrent task. They were instructed to walk at their self-selected pace while looking at a fixation cross in front of them. Subsequently, participants' cognitive–motor dual tasking was assessed. Children were asked to walk across the electronic pathway eight times while performing each executive function task (adding up to a total of 24 walks). They saw the identical stimuli as in the single-task trials and were asked to say their answer out loud. Children were not instructed to prioritize one task over another. Finally, children were asked to once more sit in the chair and solve the second half of single-task trials (the last four trials) in each executive function task with individually adjusted difficulty levels. The reason for splitting children's single-task performance into two sets presented before and after dual-task performance was to disentangle effects of learning from effects of single versus dual tasking (for a similar procedure, see Schaefer, Jagenow, Verrel, & Lindenberger, 2015). Order of the executive function tasks was counterbalanced in single- and dual-task conditions using a Latin square.

Adjustment of the executive function tasks

Prior to the cognitive single tasks, we aimed to adjust participants' performance level in each task to a comparable success rate of approximately 90% compared with their baseline performance in a low-difficulty condition (Saxena et al., 2017; Schaefer et al., 2008). By doing so, we aimed to create a comparable cognitive load for participants across the executive function tasks during the dual-task condition. Participants sat in a chair in front of the presentation. After familiarizing children with the respective executive function task in the practice trials, they were presented with Level 1 trials with identical presentation times and interstimulus intervals (ISIs) as in the practice trials (for four trials). We counted participants' errors when solving these trials (e.g., a child produced one error in four trials consisting of 48 items). Then, in a following set of Level 2 trials, we manipulated task difficulty by decreasing presentation times and ISIs. By presenting the stimuli more quickly, we aimed at lowering participants' performance to an approximate level of 90% as compared with their performance in the preceding Level 1 trials (e.g., a participant producing one error in the first set of Level 1 trials would be expected to produce approximately five errors within this set of Level 2 trials). If this number of errors was not met, participants were presented with another set of Level 3 trials with even faster presentation times and ISIs. Therefore, in line with previous research (Schaefer et al., 2008), higher performance in previous trials resulted in lower presentation times and ISIs in the following trials and thus increased task difficulty until individual performance was adjusted to approximately 90% of their baseline Level 1 performance. Using this manipulation, children's performance levels could be lowered to comparable levels in all three executive function tasks (for means and standard deviations, see Table 1; $F = 1.45$, $p = .24$, $\eta_p^2 = .01$).

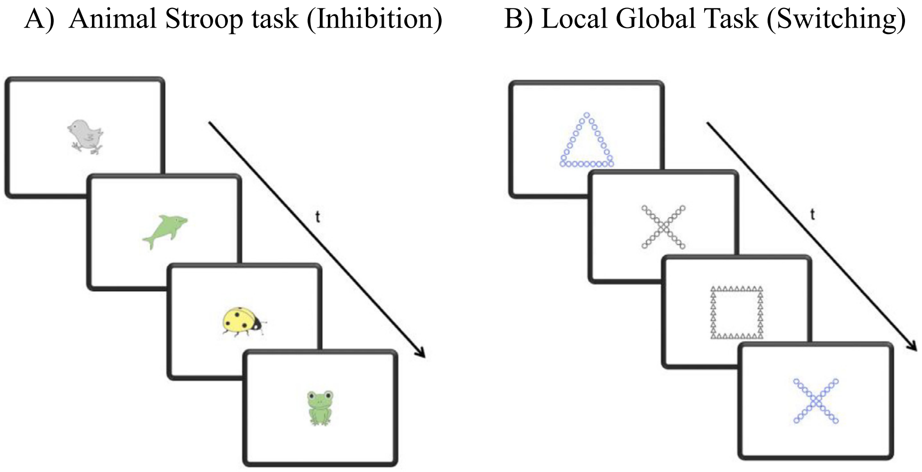

Fig. 1. Examples of the stimuli used in the animal Stroop task (A) and the local–global task (B). Correct answers presented: (A) yellow, blue, red, green; (B) triangle, circle, triangle, cross. t, presentation time. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Statistical analyses

Gait parameters were scanned for outliers (mean ± 3 *SD,* amounting to 1.56%), and these values were excluded. Then, we computed gait parameters such as CV stride time (*SD* stride time / mean stride time × 100). Given the nested structure of our data (24 walks in each individual child), we used a multilevel modeling approach that takes this interdependence into account. We used a two-level approach, with Level 1 referring to variations in the key variables across different walks (e.g., CV stride time, dual-task condition) and Level 2 representing characteristics of the individual child (e.g., age, weight, height). Age was entered as a linear continuous variable in our analyses.[2] Missing values were handled with the maximum likelihood estimation approach.

We conducted three separate models: one model with children's normalized velocity in the dual tasks, a second model with children's CV stride time in the dual tasks, and a third model with children's errors in the dual tasks (i.e., cognitive performance).[3] In all models, we included dual-task conditions as fixed and random effects on Level 1. To represent the three-category variable *executive function task,* we coded two dummy variables. Inhibition served as the reference category, with updating = 1 if walks included updating as additional task and 0 otherwise and with switching = 1 if walks included switching as additional task and 0 otherwise. Children's single-task performance (without concurrent task) was also used as a Level 1 effect to account for interindividual differences in the single tasks (which similarly controls for single-task performance as, e.g., when computing dual-task costs). In addition, we entered age, weight, height, intelligence, and sex as Level 2 effects. Age, anthropometric measures (i.e., height and weight), and intelligence were grand mean centered. As an overall test of effects of age and executive function tasks, we compared the full model as described above with the null model lacking these three additional effects (i.e., age, dummy variable updating, and dummy variable switching) but

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[2] Given that previous studies suspected nonlinear effects of age on cognitive–motor dual tasking (e.g., Ruffieux et al., 2015), we repeated our analyses using age squared as a continuous variable. The pattern of results remained the same.

[3] In addition, we computed the identical models using proportional dual-task costs (i.e., [dual-task performance – single-task performance] / single-task performance); for means and standard errors, see Table 1. Results remained widely similar to our findings based on dual-task performance (controlled for single-task performance), as presented in the Results section (see Appendix).

including the other terms as described above. In an additional model, we included cross-level interaction terms between age and the dummy variables of the executive function tasks and compared this full model with the more parsimonious model lacking those interactions. These interactions allowed conclusions with respect to the question of whether age is *differently* associated with dual-task ability across different executive function tasks. Multilevel analyses were conducted using SPSS 25 (IBM Corp., Armonk, NY, USA).

Results

An overview of children's demographic and anthropometric characteristics can be found in Table 1. There was a clear impact of adding age and executive function tasks to the model with children's normalized velocity as the dependent variable [full–null model comparison, $\chi^2(3) = 109.545$, $p < .001$]. As can be seen in Table 2, age was not related to children's normalized velocity in the dual tasks. However, there was an association with children's normalized velocity in the single tasks such that children who walked faster in the single tasks also walked faster in the dual tasks. With respect to differences among the executive function tasks, it was found that children walked with higher normalized velocity in the inhibition task as compared with the updating task as well as the switching task. An additional mixed linear model with two different dummy variables using updating as a reference category (dummy inhibition and switching) revealed that children walked with significantly higher velocity in switching as compared with updating ($\text{estimate}_{\text{switching}} \pm SE = .037 \pm .007$, $p < .001$).

Adding the two-way interactions between age and executive function tasks to the original mixed model did not improve model fit [$\chi^2(2) = 0.112$, $p = .946$], indicating that these interactions were nonsignificant. Therefore, it seems that age was similarly related to normalized velocity across different executive function tasks.

In the model with CV stride time as the dependent variable, it was found that adding age and the two dummy variables of executive function tasks to the model improved the model fit considerably [full–null model comparison, $\chi^2(3) = 25.952$, $p < .001$]. In contrast to the first model with normalized velocity, age was significantly related to children's CV stride time in the dual tasks such that older children walked more regularly in the dual tasks as compared with younger children even after controlling for children's gait variability in the single tasks (see Fig. 2A). Furthermore, there was an effect of sex due to girls walking with lower CV stride time as compared with boys in the dual tasks. With respect to differences among the executive function tasks, it was found that children showed higher CV stride time in the updating task as compared with the inhibition task, whereas there was no difference in CV stride time between switching and inhibition. An additional mixed linear model with two different dummy variables using updating as a reference category (dummy inhibition and switching) revealed that children walked with significantly higher CV stride time in updating as compared with switching ($\text{estimate}_{\text{switching}} \pm SE = -.133 \pm .051$, $p < .01$). Adding the two-way interactions between age and executive function tasks to the original mixed model did not improve model fit [$\chi^2(2) = 2.80$, $p = .247$], indicating that these interactions were nonsignificant. Therefore, it seems that age was similarly related to CV stride time in different executive function tasks.

In the model with children's errors in the cognitive tasks as the dependent variable, it was found that adding age and executive function tasks to the model improved the model fit considerably [full–null model comparison, $\chi^2(3) = 139.179$, $p < .001$]. Age was again significantly related to errors that children made in the dual tasks even after controlling for children's errors in the single tasks. In particular, it was found that older children made fewer errors as compared with younger children. Furthermore, children's errors in the dual tasks were positively associated with their errors in the single tasks; those children who committed many errors in the single tasks also showed more errors in the dual tasks. Children's errors were also related to children's intelligence, with children showing higher intelligence scores committing fewer errors in the dual tasks. With respect to differences among the executive function tasks, it was found that children showed a higher number of errors in the updating and switching tasks as compared with the inhibition task. An additional mixed linear model with two different dummy variables using updating as a reference category (dummy inhibition

Table 2
Effects of the variables of interest and control variables in the linear mixed models with motor and cognitive performance in the dual tasks as dependent variables.

	Normalized velocity				CV stride time				Errors			
	b	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*
Age[a]	.002	.002	[.001129, .004973]	.215	−**.015**	.004	[−.023998, −.006302]	<.01	−**.019**	.005	[−.028774, −.008614]	<.001
Executive function task (updating)[a]	−**.076**	.007	[−.090704, −.062104]	<.001	**.193**	.051	[.092617, .293222]	<.001	**.774**	.072	[.633606, .914593]	<.001
Executive function task (switching)[a]	−**.040**	.007	[−.052455, −.026800]	<.001	.060	.051	[−.039692, .158739]	.239	**.637**	.070	[.499547, .775386]	<.001
Sex (female)[a]	.002	.031	[−.059147, .062923]	.951	−**.246**	.090	[−.421934, −.068455]	<.01	−.085	.102	[−.285765, .116597]	.407
Height[a]	−.006	.004	[−.013318, −.001219]	.102	.005	.011	[−.016241, .025791]	.654	−.0004	.012	[−.024320, .023582]	.976
Weight[a]	−.00008	.003	[−.006171, .006340]	.979	−.014	.009	[−.032230, .03935]	.124	.005	.010	[−.015971, .025282]	.656
Intelligence[a]	.001	.001	[−.000629, .003338]	.179	−.001	.003	[−.006937, .004576]	.686	−**.007**	.003	[−.013307, −.000222]	.043
Single-task performance[a]	**.137**	.018	[.101363, .173040]	<.001	.029	.024	[.018051, .075995]	.227	**.155**	.017	[.121679, .187767]	<.001
Age * Executive Function task (updating)	−.00002	.0004	[−.000764, .000723]	.957	.005	.003	[−.000778, .009764]	.095	−**.023**	.004	[−.030261, −.015919]	<.001
Age * Executive Function task (switching)	−.0001	.0003	[−.000773, .000565]	.760	.002	.003	[−.003153, .007307]	.436	−**.012**	.004	[−.019115, −.005088]	<.01

Note. N = 135. CV, coefficient of variation; CI, confidence interval. Significant results are presented in bold. Age is linear and continuous.

[a] Estimates from models without interaction terms.

and switching) revealed that children showed significantly more errors in updating as compared with switching ($\text{estimate}_{\text{switching}} \pm SE = -.135 \pm .068$, $p < .05$).

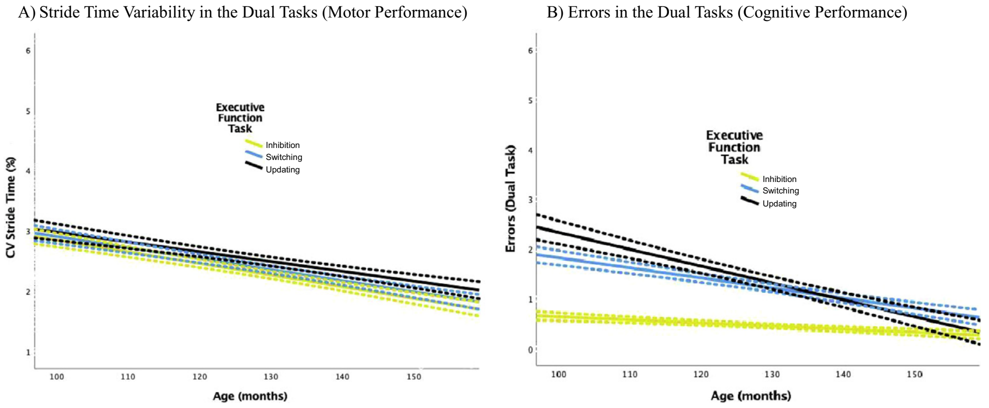
Adding the two-way interactions between age and executive function tasks to the original mixed model improved model fit considerably [$\chi^2(2) = 39.297$, $p < .001$], indicating that these interactions were significant. Therefore, it seems that in the case of children's errors, age was differently related to cognitive dual-task performance in various executive function tasks. To follow up on these interactions, we conducted separate linear mixed models as described above for each executive function task. For inhibition, it was found that age was not related to children's errors in the dual tasks (estimate ± $SE = -.005 \pm .003$, $p = .09$). By contrast, for switching and updating, age was significantly related to children's errors in the dual tasks ($\text{estimate}_{\text{switching}} \pm SE = -.025 \pm .008$, $p < .01$; $\text{estimate}_{\text{updating}} \pm SE = -.031 \pm .011$, $p < .01$) (see Fig. 2B). An additional mixed linear model with two different dummy variables using updating as a reference category (dummy inhibition and switching) revealed a significant interaction of age and the dummy variable switching (estimate ± $SE = .011 \pm .004$, $p < .01$), suggesting that the age-related decline of errors was significantly different between switching and updating.

Discussion

The current study aimed to examine age-related changes in dual-task ability across middle childhood. To this end, a large cross-sectional sample of 8- to 13-year-old children was asked to walk while solving several concurrent executive function tasks. Importantly, methodological recommendations of recent research were implemented (Saxena et al., 2017) such as adjusting and accounting for interindividual differences in children's single-task performance. After these methodological considerations were met, our findings suggested significant associations between age and children's gait variability as well as cognitive performance in the dual tasks. More concretely, it was found that older children showed a more regular gait pattern in the dual-task situations and made fewer errors, indicating their improved ability to coordinate the simultaneous tasks as compared with younger children. A similar age-related pattern was not found for children's normalized velocity, indicating that gait velocity in the dual-task situation did not differ as a function of age in our sample. These contrasting findings between our gait parameters may be explained by the considerable developmental progression of children's gait regularity across mid-childhood as opposed to gait velocity (Bril & Ledept, 1998; Hagmann-von Arx et al., 2016; Hausdorff et al., 1999; Sutherland, 1997; Sutherland et al., 1980).

Our findings are in line with those of a number of previous dual-task studies indicating similar age-related changes in children's dual-task ability (e.g., Hocking et al., 2020; Krampe et al., 2011; Schaefer et al., 2008), but they are in contrast to other findings (e.g., Anderson et al., 2011; Saxena et al., 2019). Overall, our results imply that with increasing age, children are better able to cope with two simultaneous tasks. An explanation may be found in the neurological changes that occur across mid-childhood and early adolescence such as the increased myelinization in the prefrontal cortex (Lebel & Beaulieu, 2011; Reiss, Abrams, Singer, Ross, & Denckla, 1996). This increase in white matter reflects higher connectivity and efficiency in this area of the brain. Considering that dual-task performance has been connected with activity in this particular area (D'Esposito et al., 1995; Yildiz & Beste, 2015; but see Jiang, 2004), this myelinization may explain the developmental progression in children's dual-task ability that our data imply.

Importantly, the current study may help to explain why some studies found age-related changes in children's dual-task ability, whereas others did not. We were able to show that age was differently related to children's cognitive performance in the dual tasks, whereas similar differential effects were not found for children's normalized velocity or stride time variability. Our findings showed that children's cognitive performance in the dual tasks was related to age when children performed a concurrent task tapping their updating or switching skills but not when children performed a task tapping their inhibitory skills, implying a differential effect of the type of concurrent task. This finding is remarkably consistent with previous research suggesting different developmental trajectories of executive function components (for a review, see Best & Miller, 2010). Although several studies indicated faster development of inhibitory skills (Huizinga et al., 2006; Romine & Reynolds, 2005), the development of updating and switching seems to follow a rather protracted timeline up to adolescence


A) Stride Time Variability in the Dual Tasks (Motor Performance)

B) Errors in the Dual Tasks (Cognitive Performance)

Fig. 2. Associations of age (in months) with stride time variability (coefficient of variation [CV] stride time) (A) and errors as a function of executive function tasks (B). Dashed lines indicate the lower and upper bounds of the averaged confidence intervals.

(Davidson et al., 2006; Gathercole et al., 2004; Luciana et al., 2005). Therefore, it may be that the heterogeneous findings with respect to age effects on children's dual-task ability may reflect an involvement of different executive function components in the dual tasks. That is, some of the previous dual-task studies showing no age-related changes may have involved more processes of inhibitory control (e.g., in Imbo & Vandierendonck, 2007, when inhibiting a previous automatized motor response to a tone), whereas studies that did show age-related changes may have involved more processes of updating and switching (e.g., in Hocking et al., 2020). Clearly, this post hoc explanation is speculative and needs to be addressed in future studies; however, the current study provides a unique possibility to get insight into such a differential pattern across different executive functions and may serve as an important starting point for future work.

Furthermore, results of the current study showed that several variables influenced children's dual-task ability. Our results showed that children's intelligence affected their dual-task ability. Children with higher intelligence produced fewer errors in the dual-task situations. Although this result seems rather logical given the ample evidence indicating that intelligence predicts several aspects of children's cognitive skills (Deary, 2000; Deary, Strand, Smith, & Fernandes, 2007; Geary, 2005), it should be kept in mind that influential variables on children's dual-task ability have been subject to little research as of today (for exceptions, see Hagmann-von Arx et al., 2016; Hocking et al., 2020; Möhring et al., 2019). A further influential variable was children's sex, with girls walking more regularly in the dual-task situation as compared with boys. This result was unexpected given that recent studies did not reveal any sex differences (e.g., Hagmann-von Arx et al., 2016; Hocking et al., 2020; Saxena et al., 2019). However, children diagnosed with attention-deficit/hyperactivity disorder often show concurrent deficits in the cognitive *and* motor domains (for a review, see Kaiser, Schoemaker, Albaret, & Geuze, 2015), and this disorder is more prevalent in boys as compared with girls. In relation to these findings, our results might not seem that unexpected. Future studies may assess similar sex differences in children's dual-task ability to corroborate our findings.

Even though the current study has several strengths such as a large sample and a state-of-the-art methodological approach, there are limitations that warrant mention. One limitation concerns the use of a rather homogeneous sample of typically developing, German-speaking children aged 8 to 13 years. Given that performing two simultaneous tasks is an integral part of children's everyday lives across various cultures and age groups, future studies may include samples with various cultural backgrounds. Future studies may also investigate cognitive–motor dual tasking in younger or mid-adolescence to adulthood samples. Given that inhibitory skills seem to develop faster (Huizinga et al., 2006; Romine & Reynolds, 2005) as compared with updating and switching skills, and seem to have a peak in development around middle childhood, it may be interesting to investigate how dual-task ability develops in samples younger than 8 years and thus when inhibitory skills seem to be subject to considerable development. In addition, the current study used an animal Stroop task as the indicator for children's inhibitory skills (Grob & Hagmann-von Arx, 2018), and findings may differ when using other tasks tapping inhibition. Finally, another limitation of the current study concerns the cross-sectional nature of the investigation. Naturally, the gold standard for examining development would be longitudinal in nature in order to track intra-individual developmental trajectories. To the best of our knowledge, no such study exists as of today, and thus future studies may consider a longitudinal design to answer related research questions.

Using a cognitive–motor dual task, the current study showed age-related improvements in children's ability to coordinate a cognitive task and a motor task. With increasing age, children walked more regularly in the dual-task situations and made fewer errors even after accounting for their single-task behavior, intelligence, anthropometric variables, and sex. With respect to cognitive performance, a differential pattern emerged. Whereas older children showed fewer errors in those dual tasks that involved updating or switching skills than younger children, there were no age differences in dual tasks involving inhibitory control. The current results qualify findings of previous dual-task studies (e.g., Anderson et al., 2011; Hocking et al., 2020; Krampe et al., 2011; Saxena et al., 2019; Schaefer et al., 2008) and imply that mixed results may be related to a differential involvement of executive function components in the dual task. Future studies may corroborate our findings using younger and more heterogeneous samples.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Effects of the variables of interest and the control variables in the linear mixed models with children's dual-task costs in the motor and cognitive domains as dependent variables

	Dual-task costs (normalized velocity)				Dual-task costs (CV stride time)				Dual-task costs (errors)			
	b	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*
Age[a]	–.001	.001	[–.00337, .000686]	.193	–**.009**	.003	[–.01407, –.00379]	<.01	–**.010**	.003	[–.01562, –.00346]	<.01
Executive function task (updating)[a]	**.048**	.005	[.03918, .057603]	<.001	**.118**	.031	[.05717, .17812]	<.001	**.629**	.049	[.53337, .724778]	<.001
Executive function task (switching)[a]	**.026**	.004	[.01735, .034042]	<.001	.042	.031	[–.01823, .10194]	.172	**.318**	.048	[.22374, .412514]	<.001
Sex (female)[a]	.001	.021	[–.03949, ..04163]	.958	–**.138**	.052	[–.24023, –.03491]	<.01	–.063	.061	[–.18407, .058628]	.308
Height[a]	.004	.002	[–.00035, .009311]	.069	.006	.006	[–.00652, .017886]	.359	.003	.007	[–.01185, .017043]	.723
Weight[a]	–.0004	.002	[–.00455, .003769]	.854	–.010	.005	[–.02047, .00053]	.063	–.001	.006	[–.01365, .011235]	.848
Intelligence[a]	–.001	.0007	[–.00235, .000292]	.126	–.0001	.002	[–.00347, .003222]	.943	–.003	.002	[–.00687, .001023]	.145
Single-task performance[a]	**.489**	.012	[.46525, .513086]	<.001	–**.597**	.015	[–.62659, –.56692]	<.001	–**.319**	.012	[–.3426, –.29604]	<.001
Age * Executive Function task (updating)	.00003	.0003	[–.000448, .000510]	.899	.003	.002	[–.000602, .005759]	.112	–**.011**	.003	[–.016241, –.006389]	<.001
Age * Executive Function task (switching)	.00003	.0003	[–.000409, .000462]	.905	.001	.002	[–.002109, .004231]	.511	–.005	.002	[–.009505, –.000166]	.058

Note. N = 135. CV, coefficient of variation; CI, confidence interval. Significant results are presented in bold. Age is linear and continuous. Dual-task costs = (dual task – single task) / single task * ±1, with (–) multiplier for gait velocity that is expected to decrease in the dual-task situation and (+) multiplier for gait variability that is expected to increase in the dual-task situation (Saxena et al., 2019). Given that some participants showed no errors in the single task, it was impossible to calculate cognitive dual-task costs. Here, we followed common practice and added a constant to the original data (+1) in each executive function task in order to compute cognitive dual-task costs.

[a] Estimates from models without interaction terms.

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