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ORIGINAL ARTICLE

Cognitive control processes associated with successful gait performance in dual-task walking in healthy young adults

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Abstract

Growing evidence suggests that the reliance on cognitive control processes during normal walking increases as the locomotor task gets more complex and challenging. The aims of the present study were to explore the (negative) effects of smartphone gaming on gait performance in healthy young adults, and to identify cognitive resources that might help to maintain high gait performance during dual-task walking. Gait speed and gait variability during walking at a self-selected comfortable speed were assessed in 40 healthy, young adults, and compared between single-task and dual-task walking (i.e., concurrent smartphone gaming) in undisturbed, simple and more challenging walking environments (i.e., stepping over an obstacle while walking). Based on single-task performance, dual-tasking costs were computed and linked to higher-level cognitive control processes, which were assessed for each individual. Cognitive function testing encompassed tests on the mental representation of the gait, working memory capacity, inhibitory control and cognitive flexibility. Our data revealed that gaming on a smartphone while walking strongly affected participants' gait performance (i.e., up to 26.8% lower gait speed and 60.2% higher gait variability), and decrements in gait performance were related to higher cognitive control processes. Cognitive resources that were associated with performance decrements in dual-task walking include response inhibition, cognitive flexibility, working memory, and a well-structured mental representation of the gait. From that, it appears that even in healthy young adults better cognitive resources may help to maintain high gait performance in situations, in which we have to deal with dual- or multi-task demands (e.g., using a smartphone) while walking.

Introduction

Growing evidence suggests that the reliance on cognitive control processes during normal walking, which is usually seen as a highly automatized motor skill, increases as the locomotor task gets more complex and challenging (see Al-Yahya et al., 2011; Yogev-Seligmann, Hausdorff, & Giladi, 2008 for reviews). This has been mostly derived from studies on dual-task walking, which consistently have found that gait performance is negatively affected in dual-tasking situations (Beurskens & Bock, 2012; Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016; Kelly, Janke, & Shumway-Cook, 2010). In detail, researchers reported reduced gait speed and stride length, and increased stride time and gait variability for dual-task as compared to single-task walking (e.g., Amboni, Barone, & Hausdorff, 2013; Beurskens et al., 2016; Kelly et al., 2010; Yogev-Seligmann et al., 2008).

As dual-tasking costs (DTC) during walking may easily become a major safety issue in everyday life (Lamberg & Muratori, 2012; Montero-Odasso, Verghese, Beauchet, & Hausdorff, 2012; Nasar, Hecht, & Wener, 2008), they have been studied and described extensively in various populations during the last decade. However, although it is widely accepted that cognition plays a key role for gait control, findings linking individual cognitive function to gait performance in dual-task walking are merely restricted to patient populations or older adults (see Amboni et al., 2013; Montero-Odasso et al., 2012; Morris, Lord, Bunce, Burn, & Rochester, 2016; Yogev-Seligmann et al., 2008 for reviews). In the present study, we therefore, investigated whether DTC during dual-task walking in healthy young adults can be predicted from individual cognitive functions to better understand in how far limited cognitive resources may account for impairments in gait performance during dual-task walking. That is, the present study might help to forward our understanding of a general contribution of cognitive function to

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gait performance as opposed to the study of impaired gait performance and cognitive dysfunction.

In that regard, recent findings indicated that the implementation of a secondary task during normal walking results in an increased neural activation of brain areas that are associated with executive function and attention (e.g., frontal brain regions; cf. Beurskens et al., 2016; Holtzer et al., 2011), what is indicative of increased cognitive demands during dual-task walking. In line with this finding, performance decrements during dual-task walking as compared to undisturbed walking have traditionally been explained with limited cognitive resources (i.e., central capacity), for which both tasks compete when they share the same neural networks (Craik & Bialystok, 2006; Pashler & Johnston, 1998; Woollacott & Shumway-Cook, 2002). That is, DTCs may be regarded as the result of insufficient cognitive resources (i.e., central capacities) to cope with the increased cognitive load implemented by the secondary task. The core executive functions, working memory, inhibitory control and cognitive flexibility (see Diamond, 2013 for a review), reflect such higher cognitive control processes (called cognitive resources or central capacity here) required to coordinate concurrent task demands (i.e., to cope with the increased cognitive load due to DT demands, and to help to adapt or compensate to these situations). As such, we assumed that better executive functions help to cope with the increased cognitive load induced by the secondary task during dual-task walking. More specifically, we hypothesized that better cognitive functions are associated with lower DTC during dual-task walking in healthy young adults.

In the present study, we used gaming on a smartphone as the secondary task, which nowadays is probably one of the most common dual-task situations in everyday life. Research demonstrated strong negative effects of cell phone use on gait performance, especially during manually controlling the phone (e.g., texting or gaming) while walking (e.g., Lamberg & Muratori, 2012; Lim, Amado, Sheehan, & Van Emmerik, 2015; Plummer, Apple, Dowd, & Keith, 2015). As with other dual-tasks, cell phone use has been associated with an increased cognitive load and a reduced situational awareness (i.e., proper perception and processing of environmental cues; cf. Hyman, Boss, Wise, McKenzie, & Caggiano, 2009; Lim et al., 2015; Nasar & Troyer, 2013). As such, we hypothesized that negative effects on gait performance, and reliance on cognitive control, would be higher in walking situations that require constant monitoring of the walking environment (e.g., to avoid bumping into obstacles) as compared to simple walking situations in which relying on automatized behavior is sufficient.

Methods

Participants

Forty healthy young adults (age range = 19–32 years, mean age = 23.8 ± 2.8 years; 20 men; mean height = 176.1 ± 7.5 cm; mean weight = 69.9 ± 10.6 kg) volunteered in this study. On average, participants engaged in 7.2 (± 3.4) h of physical activity per week, used a computer (including smartphones, tablets, etc.) 3.3 (± 2.1) h per day and played video games for 2.5 (± 4.3) h per week. Subjects with a history of neurological and/or mental disorders, and participants with known musculoskeletal and neuromuscular disorders that limit function of their lower extremities were excluded from the study. The study was approved by the local institutional review board at the University of Rostock and conformed to the declaration of Helsinki. Prior to participation, written informed consent was obtained from all participants.

Measures and procedure

All participants completed a walking task under conditions of different complexity and a comprehensive assessment of cognitive performance using well-established standard tests within a single 1.5 h testing session. The cognitive functions tested were working memory capacity, inhibitory control, cognitive flexibility and the long-term memory structure of the gait. Gait performance, i.e., gait speed and gait variability, during walking at self-selected comfortable speed was assessed and compared between single- and dual-task walking conditions in a simple and challenging walking environment, respectively. All participants were tested individually in two different, quiet rooms (i.e., one for the cognitive tests and one for the walking tests) with no auditory or visual interference. All walking tests and cognitive tests were administered in a randomized order.

Experimental tasks

Gait performance was assessed in single- and dual-task conditions. During *single-task walking*, participants were asked to walk at a self-selected comfortable speed. During *dual-task walking*, participants were playing a stroop-like game on a smartphone (Huawei P8 Lite, Huawei, Shenzhen, China) while walking at a self-selected comfortable speed. Both single- and dual-task walking conditions were performed in a simple and a challenging walking environment: In the *simple walking environment* participants were walking in a straight line without any distractions. In the more *challenging walking environment* participants were

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required to step over a wooden obstacle (20 cm in height, 30 cm in length) randomly placed between 4.20 and 4.70 m on the walkway while walking at a self-selected comfortable speed. The obstacle dimensions (i.e., just higher than the standard stair rise, and wide enough to adjust step length) were chosen as to make sure that young adults have to make active adjustments (i.e., actively allocate attention to the walking task) to successfully master the walking task. Participants were instructed not to hit the obstacle, and none of them did.

Gait performance was measured using the OptoGait floor-based photocell system (Microgate, Bolzano, Italy) as described previously (Jacksteit et al., 2018; Stöckel et al., 2015). Six transmitting and six receiving bars were placed parallel to each other with a distance between the bars of 1 m. Each bar contains 96 LEDs communicating on an infrared (visible) frequency with the opposite bar. The patient's movement interrupts the communication between the LED's and the position can be measured with a resolution of 1.041 cm. Subjects were instructed to walk along the 6-m walkway at self-selected comfortable gait speed, starting and finishing each walk 2 m before and after the walkway. Participants wore their own closed shoes with heel height not exceeding 3 cm (Kressig, Beauchet, & European GAITRite Network Group, 2006). The data were sampled at 1 kHz and analyzed using the OptoGait software (version 1.8.0.0., Microgate, Bolzano, Italy) and a custom-written excel spreadsheet (Excel 2010, Microsoft Inc., Seattle, USA). In each walking condition participants performed 12 trials comprised of 3 familiarization (to rule out learning effects) and 9 test trials. The mean value across the nine test trials was calculated for each gait parameter. The order of the walking conditions was randomized. Stride length was calculated as the distance between the heel positions of two subsequent footprints of the same foot. Primary outcome measures of gait performance were the height-adjusted gait speed and the stride-to-stride variability (coefficient of variation for stride length; $CV = \text{standard deviation} \times \text{mean}^{-1} \times 100$).

The stroop-like game *True Color* (Hubert, 2015) required participants to decide as fast as possible whether a colored circle matches the name of a color written in the circle, thereby not getting distracted by the color of the word. The phone was held in one hand, while the index finger of the other hand was to be used to touch the "yes" or "no" buttons on the touchscreen as fast as possible. Each game lasted 30 s and participants began playing before they started walking (2 m before the walkway) and they had to finish the game (about 10 s) even when being finished walking (2 m behind the walkway). In a single-task gaming condition, participants played the game standing in an undisturbed area of the room. The total number of correct decisions within 30 s averaged across all trials per condition (i.e., single-task, simple, challenging) was used as the gaming score. This type of secondary task was used to induce a cognitive interference while walking.

Cognitive function measures

Cognitive performance was assessed using a variety of well-established and commonly used standard tests covering the core executive functions (as key processes of cognitive control) described by Diamond (2013). All tests were built and run using the PEBL software v0.14 (Mueller & Piper, 2014; see Piper et al., 2012 for validation). Participants' mental representation of the gait was assessed using the structural dimensional analysis of mental representations (cf. Jacksteit et al., 2018, 2019; Stöckel et al., 2015).

Working memory In the *Corsi block-tapping test* (Corsi, 1972; Kessels, van Zandvoort, Postma, Jaap Kappelle, & de Haan, 2000), a measure of visuospatial working memory capacity, a set of blue blocks arranged in a static spatial array (on black background) changed color from blue to yellow in a predetermined sequence. Participants were asked to reproduce the sequence by tapping on the blocks in the same order they lit up. The test started with three blocks to be tapped and increased by one block up to a maximum of nine blocks every time the participant correctly reproduced the sequence in at least one out of two trials. When two trials of a given span length were failed, the test was discontinued. The memory span, i.e., the maximum sequence length that resulted in correct recall in 50% of the trials was used as primary outcome measure.

Inhibitory control Inhibitory control at the level of response selection was assessed using a *Simon Task* (Hommel, 2011; Lu & Proctor, 1995). In this test participants were sitting in front of a computer screen, on which either a red or blue circle showed up in the middle, on the right or the left side of the screen. At the start of each trial a fixation cross was presented for 400 ms, after which a red or blue circle appeared on the screen. Participants were told to press the left shift key when they see the red circle and the right shift key when they see the blue circle as fast as possible, ignoring the location of the stimulus. Trials in which the stimulus location was on the same side as the required response were congruent, trials in which the stimulus location was on the opposite side as the required response were incongruent, and trials in which the stimulus location was in the middle of the screen were neutral. The experiment consisted of 140 trials (60 congruent, 60 incongruent, 20 neutral) presented in a randomized order. Trials faster than 250 ms and slower than two standard deviations above the individual mean were excluded from analysis. Mean reaction time residuals (cf. Salthouse, 2010; Stuhr, Hughes, & Stöckel, 2018) in incongruent trials (red circle appears at the

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right side of the screen, blue circle appears at the left side of the screen), controlled for the mean reaction time in congruent trials (stimulus location and response key are on the same side) as an indicator of task-specific processing speed and response accuracy in incongruent trials, were used as measure of response inhibition.

Selective attention (also described as interference control) was assessed using a standard *Flanker task* (Eriksen & Eriksen, 1974; Stins, Polderman, Boomsma, & de Geus, 2008). At the start of each trial, a fixation cross was presented for 500 ms, after which five arrows arranged in a horizontal array appeared for 800 ms. Participants were asked to respond as quickly as possible to the direction the central arrow was pointing to (ignoring the flanking arrows) by pressing the right or left shift keys on a standard keyboard. In the congruent condition, the flanking arrows all pointed in the same direction as the central arrow, in the incongruent condition the flanking arrows pointed in the opposite direction as the central arrow, and in the neutral condition the central arrow was surrounded by two dashes on either side of the arrow or no distractor at all. There were eight unique conditions comprising the factors condition (congruent, incongruent, neutral 1, neutral 2) and arrow direction (left, right). Each condition was performed ten times, yielding a total of 80 trials. All trials were fully randomized. Trials faster than 250 ms and slower than two standard deviations above the individual mean were excluded from analysis. Mean reaction time residuals (cf. Salthouse, 2010; Stuhr et al., 2018) for incongruent trials, controlled for the mean reaction time in congruent trials (as an indicator of task-specific processing speed) and response accuracy in the incongruent trials, were used as measure of selective attention.

Cognitive flexibility In the *Wisconsin Card Sorting Test (WCST)*, a test to assess participants' cognitive flexibility (Grant & Berg, 1948) or more specifically their *set shifting* abilities (Gläscher et al., 2012) participants were asked to sort a total of 128 cards onto one of four piles of stimulus cards by matching the color, the shape or the number of symbols on the cards. Participants were not informed about the classification rule, but they received feedback after each trial whether the respective card was correctly classified according to the current rule ("correct" or "incorrect"). After ten consecutive cards had been sorted correctly the classification rule changed without warning and participants had to adopt the new rule as quickly as possible. The percentage of perseverative errors (i.e., errors in which the participant used the same rule as in the previous trial) was used as measure of participants' ability to flexibly adapt to a new rule and give up an old rule.

The *Trail Making Test* (TMT; Bowie & Harvey, 2006; Reitan & Wolfson, 1995) was also used as a measure of cognitive flexibility tapping, however, more into participants' *response shifting* abilities (Gläscher et al., 2012; Sánchez-Cubillo et al., 2009). In part A participants were asked to connect 25 numbers in ascending order as quickly as possible. In part B participants were asked to connect 25 numbers (in ascending order) and letters (in alphabetical order) in an alternating fashion (i.e., 1-A-2-B-3-C, etc.). Testing and trouble-shooting followed the descriptions by Bowie and Harvey (2006). The time to complete part B, controlled for time to complete part A (as indicator of task-specific processing speed), was used as measure of response shifting (TMT-B_A).

Gait-specific mental representation The gait-specific mental representation (MREP; i.e., the individual gait pattern as represented in one's mind) was assessed using the structural–dimensional analysis of mental representations (SDA-M), a well-established psychometric method to assess long-term memory structures of motor actions. Following the procedure described by Jacksteit et al. (2018) and Stöckel et al. (2015), the eight functional periods initial contact, loading response, mid-stance, terminal stance, preswing, initial swing, mid-swing and terminal swing as basic action concepts (BACs) of the human gait were entered into the splitting procedure. The splitting procedure, during which participants were asked to classify pictures of all combinations of any two BACs as similar or dissimilar (by pressing left and right navigation keys for "yes" or "no", respectively), was presented to the participants on a 17-inch monitor in a quiet room. Based on the decisions during the splitting procedure, a Euclidean distance matrix between all BACs was calculated. A hierarchical cluster analysis was then applied to compute the individual mental representation structures of the gait (as stored in long-term memory). Finally, these structures were compared to the grouped cluster solution of the healthy young adults from Stöckel et al. (2015) as a reference structure to unveil structural differences of the individual cognitive representation of the gait from an average pattern of healthy young adults. Comparisons of the cluster solutions were performed by determining the structural invariance (λ) between the reference structure and the individual cluster solutions (for more detail regarding SDA-M, see Schack, 2012 and Supplementary Material to Stöckel, Hughes, & Schack, 2012).

Data analysis

Preliminary analyses were conducted on all relevant measures to check for normality, sphericity (Mauchly test), univariate and multivariate outliers, with no serious violations noted. To study the effects of the concurrent cognitive interference task on gait performance in the simple and more challenging walking environment we ran separate analyses of variances (ANOVA) for gait speed and gait variability

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with task (single vs. dual) and walking environment (simple vs. challenging) as within-subject factors. Additionally we ran a separate ANOVA comparing the gaming performance between single-task gaming, smartphone gaming while walking (simple environment) and smartphone gaming while walking in a challenging walking environment to estimate the effect of walking and the need of stepping over an obstacle on the secondary gaming task. Data are reported as mean (M) and standard deviation of the mean (SD), as well as mean difference (MD) along with 95% confidence interval of the mean (95% CI). Partial eta-squared (η_p^2) is reported as measure of effect size.

To understand the role of cognitive control processes for gait performance under single- and dual-task conditions, correlation statistics (Pearson *r*) were computed between measures of individual cognitive functioning and measures of gait performance (height-adjusted gait speed, stride-to-stride variability) and secondary task performance (gaming scores), as well as DTC during dual-task walking. Dual-task costs (DTC) reflecting the decrements in gait performance (i.e., percent decrease in gait speed and increase in gait variability) and gaming performance (i.e., percent decrease in gaming score) as a result of the concurrent cognitive interference tasks were computed as described earlier (DTC = [dual-task performance – single-task performance] × single-task performance^{-1}; cf. Beurskens & Bock, 2012). Mean dual-task costs (mDTC; i.e., percent decrease averaged across the decline in gait speed and gaming performance in the smartphone-distracted conditions), were used as a measure of DTCs irrespective of individual task priorities (Beurskens & Bock, 2012). Correlation coefficients between 0.1 and 0.3 were defined as small, between 0.3 and 0.5 as moderate and of 0.5 and above as strong correlations (Cohen, 2013). Subsequently multiple regression analyses were employed to identify the main predictors of the decrease in gait performance (i.e., DTCs for gait speed and gait variability) when being confronted with a secondary cognitive task during walking, and to study the relative strength of these predictors when controlling for the others. Therefore, all measures of cognitive functioning were entered into the regression equation as potential predictors. The level of significance was established at $p \leq 0.05$. All analyses were performed using SPSS statistical package 20.0.

Results

Means and standard deviations for single- and dual-task walking (and gaming) in simple and challenging walking environments are presented in Table 1.

Gait performance under single- and dual-task conditions

Effects of concurrent gaming while walking on gait speed

A *task* (single vs. dual) × *walking environment* (simple vs. challenging) ANOVA for gait speed revealed a significant main effect for task, F (1,39) = 231.99, $p < 0.001$, $\eta_p^2 = 0.86$, but no task × walking environment interaction, F (1,39) = 2.84, $p = 0.10$, $\eta_p^2 = 0.07$. Post hoc analysis revealed that gait speed was significantly lower in the dual-task walking conditions (i.e., gaming while walking) as compared to single-task walking (MD = − 0.19, 95% CI − 0.22, − 0.17) in both simple and challenging walking environments. Gait speed was not significantly affected by the presence of an obstacle in the more challenging walking environment, F (1,39) = 3.61, $p = 0.07$, $\eta_p^2 = 0.09$. The decrease in gait speed (DTC) as a result of concurrent smartphone gaming in the dual-task walking conditions as compared to single-task walking is highlighted in Fig. 1.

Table 1 Walking and gaming performance in single-task (ST) and dual-tasking (DT) conditions and in simple and challenging environments: (1) single-task walking (task: single; environment: simple); (2) gaming while walking (task: dual; environment; simple); (3) walking over an obstacle (task: single; environment: challenging); (4) gaming while walking over an obstacle (task: dual; environment: challenging)

	Condition	Mean	SD
Height-adjusted gait speed (1/s)	Single-task walking (ST)	0.74	0.09
	Gaming while walking (DT)	0.54	0.12
	Walking over an obstacle (ST)	0.74	0.10
	Gaming while walking over an obstacle (DT)	0.55	0.12
Stride-to-stride variability (%)	Single-task walking (ST)	2.30	0.69
	Gaming while walking (DT)	3.52	1.19
	Walking over an obstacle (ST)	7.25	1.73
	Gaming while walking over an obstacle (DT)	9.56	2.20
Gaming score	Single-task gaming (ST)	33.23	3.55
	Gaming while walking (DT)	30.54	3.88
	Gaming while walking over an obstacle (DT)	31.76	3.74

Higher gait speed, lower stride-to-stride variability and higher gaming scores indicate better performance. Displayed are means and standard deviations (SD)

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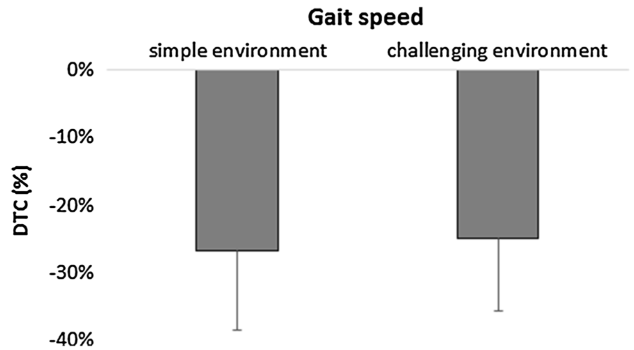

Fig. 1 Dual-tasking effects on gait speed. Percent decrease in height-adjusted gait speed in dual-task walking (as compared to single-task walking) in simple and more challenging walking environments. Single-task walking gait speed was reduced by 0.12 ± 3.91% in the challenging as compared to the simple walking environment. Lower values indicate higher dual-tasking costs (DTC). Error bars indicate standard deviation of the mean

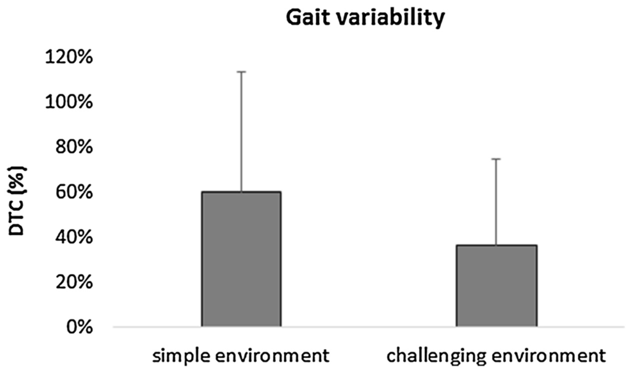

Fig. 2 Dual-tasking effects on gait variability. Percent increase in stride-to-stride variability in dual-task walking (as compared to single-task walking) in simple and more challenging walking environments. Single-task walking gait variability increased by 235.21 ± 97.41% in the challenging as compared to the simple walking environment. Higher values indicate higher dual-tasking costs (DTC). Error bars indicate standard deviation of the mean

Effects of concurrent gaming while walking on gait variability

A *task* (single vs. dual) × *walking environment* (simple vs. challenging) ANOVA for gait variability revealed significant main effects for the factors walking environment, F (1,39) = 495.40, $p < 0.001$, $\eta_p^2 = 0.93$, and task, F (1,39) = 62.28, $p < 0.001$, $\eta_p^2 = 0.62$, and an interaction effect between the two factors, F (1,39) = 9.92, $p = 0.003$, $\eta_p^2 = 0.20$. Post hoc analysis revealed that single-task walking in a more challenging walking environment resulted in a strong increase in gait variability as compared to single-task walking in a simple walking environment without obstacles (MD = 4.95%, 95% CI 4.43, 5.47; $p < 0.001$). Concurrent gaming while walking (i.e., dual-tasking), however, only resulted in a slight increase in gait variability in either walking environment (MD = 1.77%, 95% CI 1.32, 2.22; $p < 0.001$). The increases in gait variability (DTC) as a result of concurrent smartphone gaming in the dual-task walking conditions as compared to single-task walking are shown in Fig. 2.

Gaming performance under single- and dual-task conditions

Another ANOVA compared the gaming performance between single-task gaming, gaming while walking (simple environment) and gaming while walking in a more challenging walking environment. The analysis yielded at significant differences between the three gaming conditions, F (2,78) = 11.96, $p < 0.001$, $\eta_p^2 = .24$. Post hoc analysis revealed that gaming performance was significantly higher in single-task gaming as compared to gaming while walking in a simple walking environment (MD = 2.69, 95% CI 1.23, 4.14; $p < 0.001$) and gaming while walking in a more challenging walking environment (MD = 1.47, 95% CI 0.06, 2.88; $p = 0.04$) (see Table 1). Adding an obstacle did not significantly affect gaming performance during walking ($p = 0.06$) (see Table 1). DTC for gaming performance are shown in Fig. 3.

Analysis of DTC averaged across decrements in gait speed and gaming, i.e., irrespective of individual task priorities (cf. Beurskens & Bock, 2012), revealed mean costs of − 17.24 ± 8.59% and − 14.44 ± 7.96% for dual-task walking in simple and challenging walking environments, respectively.

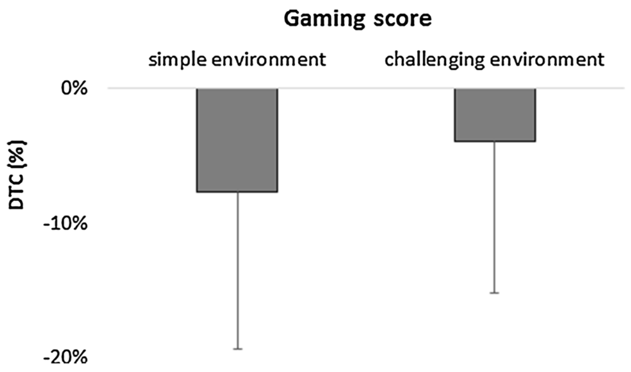

Fig. 3 Dual-tasking effects on gaming performance. Percent decrease in gaming performance during dual-task walking in the simple and more challenging walking environments as compared to single-task gaming. Lower values indicate higher dual-tasking costs (DTC). Error bars indicate standard deviation of the mean

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Associations between dual-tasking costs in gait performance and individual cognitive functioning

To examine whether the reported DTC during walking are associated to specific, individual cognitive resources, we performed correlation analyses between cognitive functions, DTC and single-task performance. For dual-task walking, correlations were controlled for single-task gaming performance to consider the fact that better gaming performance might be related to better cognitive functions, and/or more resources that can be used for the walking task. Means and standard deviations for the cognitive function measures are presented in Table 2. Raw correlations are presented in Table 3.

Table 2 Descriptive statistics for measures of cognitive functioning

	Mean	SD
Working memory, Corsi block-tapping, memory span	5.74	0.79
Response inhibition, Simon task		
Congruent condition, RT (ms)	434.67	80.03
Congruent condition, accuracy (%)	98.60	2.24
Incongruent condition, RT (ms)	481.26	83.74
Incongruent condition, accuracy (%)	93.03	4.99
Selective attention, Flanker task		
Congruent condition, RT (ms)	407.53	71.26
Congruent condition, accuracy (%)	95.63	11.16
Incongruent condition, RT (ms)	448.41	100.17
Incongruent condition, accuracy (%)	88.75	21.89
Set shifting, Wisconsin card sorting		
Percent success (%)	83.86	5.61
Perseverative errors (%)	10.69	2.34
Response shifting, trail making test		
Part A (s)	14.86	4.09
Part B (s)	31.38	10.70
Mental representation of the gait (Λ)	0.53	0.03

RT reaction time, *ms* milliseconds, *s* seconds

Data analysis revealed that decrements in gait performance during dual-task walking (as compared to single-task walking) were significantly related to set shifting abilities, response inhibition and the gait-specific long-term memory representation (see Table 3). For dual-task walking in a simple walking environment, lower DTC were associated with better set shifting abilities, a better gait-specific mental representation (i.e., closer to the ideal memory structure) and better response inhibition (i.e., faster reaction times). For dual-task walking in a more challenging walking environment, lower DTC were associated with a better gait-specific mental representation (i.e., closer to the ideal memory structure) and better response inhibition (i.e., faster reaction times).

Similarly, mean DTCs (i.e., averaged across costs in gait speed and gaming performance) during dual-task walking in simple and more challenging walking environments were negatively related to set shifting (i.e., rate of perseverative errors; both r's > -0.37, p's < 0.009) and positively related to the mental representation of the gait (both r's > 0.30, p's < 0.03). That means that the average DTCs were smaller in individuals with better set shifting abilities and a better gait-specific mental representation (i.e., closer to the ideal memory structure). Cognitive functions were, however, not significantly associated with single-task gait performance and decrements in dual-task gaming performance.

Multiple regression analysis did not reach significance for gait speed DTCs ($R^2 = 0.26$, $F(6,32) = 1.83$, $p = 0.13$). However, analyses revealed that cognitive functions were a significant predictor for gait variability DTCs during dual-task walking ($R^2 = 0.34$, $F(6,32) = 2.77$, $p = 0.03$). Working memory capacity ($\beta = -0.33$, $t(38) = -2.28$, $p = 0.03$), response inhibition ($\beta = 0.38$, $t(38) = 2.41$, $p = 0.02$) and mental representation of the gait ($\beta = -0.32$, $t(38) = -2.01$, $p = 0.05$) accounted for 11.2%, 14.8% and 10.1% of the

Table 3 Raw correlations between (simple) single-task walking as well as dual-task walking and gaming costs (DTC, i.e., percentage of loss in performance), and cognitive functions

	Single-task walking		Dual-task walking					
			Simple environment			Challenging environment		
	Speed	CV	Speed costs	CV costs	Gaming costs	Speed costs	CV costs	Gaming costs
Working memory$_{\text{(memory span)}}$	−0.15	0.22	0.01	−0.23	−0.20	0.02	−0.18	−0.24
Response inhibition$_{\text{(RT residuals)}}$	0.25	−0.16	−0.04	**0.43****	−0.07	0.03	**0.32***	−0.08
Selective attention$_{\text{(RT residuals)}}$	−0.21	−0.03	0.15	0.01	−0.19	0.19	0.05	−0.08
Set shifting$_{\text{(error rate)}}$	0.18	0.06	**−0.36***	0.05	−0.19	−0.26	−0.09	−0.28
Response shifting$_{\text{(time residual)}}$	0.17	0.03	−0.11	−0.003	−0.02	0.13	−0.09	−0.14
Mental representation of the gait$_{\text{(Lambda)}}$	0.12	−0.14	0.27	**−0.36***	0.18	**0.33***	−0.25	0.17

RT reaction time, *CV* coefficient of variation

*$p < 0.05$ and **$p < 0.01$ denote significant relations (bold-typed)

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variance in dual-tasking-related costs in gait variability, respectively. Although not statistically significant, a statistical trend indicated that mDTCs for gait speed and gaming performance during dual-task walking can in part be accounted for by individual cognitive functions ($R^2=0.30$, F (6,32) = 2.23, $p=0.06$). In particular, cognitive flexibility ($\beta = -0.41$, t (38) = − 2.48, $p=0.02$) and the mental representation of the gait ($\beta=0.38$, t (38) = 2.35, $p=0.03$) accounted for 16.7% and 14.8% of the variance in mean dual-tasking-related costs in gait speed and gaming performance, respectively.

Discussion

The purpose of the present study was to examine whether (and if so, which) individual cognitive functions (i.e., resources) account for the performance decrements during dual-task walking in healthy young adults. To achieve this, we assessed gait and secondary task performance of forty healthy young adults under single- and dual-task conditions (gaming: absent vs. present) in a simple and a more challenging (obstacle: absent vs. present) walking environment, and correlated DTCs with individual cognitive functions. Our data revealed that (a) gaming on a smartphone while walking strongly affected gait performance (i.e., lower gait speed and higher gait variability), and (b) decrements in gait performance were related to higher cognitive control processes.

In detail, we found that gait (and gaming) performance was significantly reduced during dual-task walking as compared to single-task walking (and gaming). Mean DTCs averaged across the decrements in gait speed and gaming performance ranged between 14.5 and 17.2%. More specifically, gait speed decreased by 26.8% and 24.9%, gait variability increased by 60.2% and 36.7%, and gaming performance decreased by 7.7% and 3.9% in simple and more challenging walking environments, respectively. Although the reduction in gait speed during dual-task walking appears quite high for healthy young adults, it is well in line with previous studies using manual tasks with a high demand on visual-spatial control in general (see Beurskens & Bock, 2012 for a review), or texting on a cell phone in particular (e.g., Lamberg & Muratori, 2012; Plummer et al., 2015) as secondary tasks. That is, the strong negative effects of smartphone gaming on gait performance are probably a result of the high cognitive load added by the secondary task. To perform successfully on both tasks individuals are required to coordinate the visuospatial information from different sources (i.e., from the smartphone to succeed in the gaming task and from the environment to maintain gait performance), which has previously been associated with higher DTC (cf. Beurskens et al., 2016; Woollacott & Shumway-Cook, 2002).

Surprisingly, smartphone gaming while walking in a more challenging walking environment, in which participants had to step over an obstacle, did not result in higher DTC as compared to gaming while walking in an undisturbed, simple walking environment. The walking environment did affect gait variability, which increased in the challenging walking environment, but this was similar for single- and dual-task walking. Unexpectedly, decrements in gait performance were even lower (although not statistically significant) in the more challenging as compared to the undisturbed, simple walking condition. This might be explained by previous findings indicating that in simple walking tasks attention is typically allocated to the secondary cognitive task (e.g., texting on a cell phone; Lopresti-Goodman, Rivera, & Dressel, 2012; Plummer et al., 2015), while in more challenging walking tasks (e.g., narrow path) young adults prioritize the walking over the secondary task (Kelly, Eusterbrock, & Shumway-Cook, 2013). In that regard, prioritizing the walking task in the more challenging walking environment might have been more efficient in maintaining gait performance as compared to the undisturbed, simple walking environment.

Most important, DTC during dual-task walking were significantly related to cognitive functions, while single-task walking was not. This is in line with previous reports suggesting that cognitive control processes are critical in complex gait situations (e.g., when coordination of visuospatial attention is required; cf. Al-Yahya et al., 2011; Ble et al., 2005; Yogev-Seligmann et al., 2008). While Ble et al. (2005) and Yogev-Seligmann et al. (2008) restricted their findings to older adults; Al-Yahya et al. (2011) reported strong associations between cognitive function and the decrements in gait speed under dual-task conditions in their review.

Besides supporting the notion that cognitive functions are associated with dual-task performance, data of the present study provide insights into which specific cognitive functions might aid in successfully performing under dual-task conditions. Cognitive resources that were associated with performance decrements in dual-task walking (here gaming and walking) include the general abilities to flexibly adapt behavior to new situations and to quickly suppress a no longer required or inappropriate response (see Diamond, 2013; Verbruggen & Logan, 2008 for reviews), visuospatial working memory, and a well-structured mental representation of the gait (cf. Stöckel et al., 2015). That means, being successful in dual-task situations is about being able to quickly switch between the primary and the secondary task (cf. Sigman & Dehaene, 2006), i.e., allocate attention to the right task at the right time (without wasting precious resources), which was previously described as a "competition" for limited attentional resources (Woollacott & Shumway-Cook, 2002). Surprisingly, the ability to attend

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to goal-related stimuli while ignoring interfering ones (i.e., selective attention) itself was not associated to DTCs. In that regard, we argue that successful dual-task performance is not a passive process, in which one tries to protect primary task performance from the distractions of the secondary task. It's more an active process, in which individuals try to find the perfect balance between the two tasks by allocating as much attention to each task as necessary to successfully perform both tasks at the same time (for similar accounts see Meyer et al., 1995; Sigman & Dehaene, 2006). In this vein, a suitably organized, functional mental representation, usually reflecting skilled behavior that can be flexibly adopted to various situational demands (cf. Schack & Mechsner, 2006; Schack & Ritter, 2009; Stöckel et al., 2015), of either the primary or secondary task may help to deal with dual-task demands as less attention is required to execute skilled behavior, which in turn is free to use on the respective other task. Finally, better working memory might help to constantly monitor both tasks, and hold, integrate and process all the information that are necessary to perform both tasks simultaneously.

There are some limitations to the current study, which may inform future directions in this line of research. First, we only tested healthy, young adults in a very specific dual-task situation (i.e., walking and gaming) in the present study. Given remarkable changes in executive and motor function across the lifespan and task-specific associations between cognitive and motor tasks (cf. Stuhr et al., 2018), the cognitive control processes contributing to dual-task performance may differ between tasks and change as people age. The next step in this line of research would be to investigate participants from a wider developmental spectrum and in different dual-task situations (i.e., different primary and secondary tasks). Second, during dual-task walking only two-thirds of the gaming performance were affected by concurrent walking. While this difference in duration does not affect any of our main findings on how gait is affected by the secondary task and regarding the role of cognitive control processes in dual-task situations, it may affect the interpretation of gaming costs during dual-task walking. Therefore, in future studies assessment of secondary task performance should be aligned to the duration of the primary walking task to have performance measures of either task being completely affected by the respective other task. Last, the conclusions of the present study are merely based on correlation analyses. Future studies should employ designs, in which cognitive control processes are systematically manipulated (e.g., by training) to be able to draw firm conclusions on causal relations and possibilities to enhance performance in dual-task situations.

Limitations notwithstanding, findings of the present study demonstrate that higher DTCs may indeed be regarded as the result of insufficient cognitive resources (i.e., central capacities) to cope with the increased cognitive load implemented by the secondary task. Therefore, improving the executive functions working memory, set shifting and response inhibition (even in healthy young adults) is likely to result in better dual-task performance as these cognitive functions apparently represent (major parts of) the "central capacity" or "bottleneck" (e.g., Craik & Bialystok, 2006; Pashler & Johnston, 1998) that limits dual-task performance. These higher cognitive control processes develop throughout childhood (see Diamond, 2012, 2013 for a reviews), but are also known to benefit from deliberate practice across the lifespan (Diamond & Ling, 2016; Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Willis et al., 2006; Zelinski, 2009). Moreover, improving either of the two tasks in isolation to free some attentional resources probably helps to properly deal with the increased cognitive load in dual-task situations. In that regard, it is also likely that the negative effects associated with cell phone use while walking decrease the more people get used to the tasks performed on the smartphone, which would allow them allocating more attention to the walking task again. That said, it appears that better cognitive resources help to maintain better gait performance (higher gait speed, lower gait variability) in situations, in which we have to deal with dual- or multi-task demands while walking (e.g., for the optimal coordination, integration and processing of visuospatial information). At the same time, however, the flexible and dynamic prioritization (i.e., balancing) of primary and secondary task demands as described in previous work (Kelly et al., 2013; Plummer et al., 2015) seems to be an indicator of how well each task is developed and how good the individual is in switching between tasks.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standards All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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