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What affects gait performance during walking while texting? A comparison of motor, visual and cognitive factors

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ABSTRACT

Texting on a cell phone disrupts walkers' gait performance. The performance decrement has been attributed to increased motor demand, decreased visual information and increased cognitive load. However, relative contributions of motor, visual and cognitive factors are poorly understood. Here we quantitatively estimated the relative contributions of these factors by comparing multiple walking conditions. Thirty-two adults walked for 20 m, with or without a dual task on the phone. The dual task was either a cognitively demanding digit ordering task or a casual tapping task. Gait performance was assessed using gait speed, stride length, stride time and stride time variability. Results showed that texting negatively impacted gait performance. Importantly, we found that cognitive factor contributed the most, visual factor the least, and motor factor in between. Our findings resolve the inconsistency in the literature and unambiguously show that motor, visual and cognitive factors caused by simultaneous phone use all contribute to gait alterations.

Practitioner Summary: Walking performance is typically worsened when a concurrent phone use task such as texting is performed. We found that visual, motor and cognitive factors contributed to this performance decrement with increasing importance. Besides resolving inconsistency among previous reports, we also raised theoretical and practical concerns for phone use during walking.

Abbreviations: OS: operating system; WalkBase: baseline walking; WalkTapAhead: walking while performing the finger tapping task on the phone and looking ahead; WalkTapScreen: walking while performing the finger tapping task on the phone with the eyes fixated on the phone screen; WalkOrder: walking while performing a digit ordering task on the phone; OrderBase: baseline digit ordering task during still standing; CV: coefficient of variation; TC: task cost; MANOVA: multivariate analysis of variance; ANOVA: analysis of variance; LSD: least significant differences; SE: standard error

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Phone use; gait; motor control; visual distraction; cognitive load

Introduction

Cell phone use during walking is a common phenomenon nowadays, and its associated traffic accidents and injuries have dramatically increased over recent years (Langer et al. 2005; Lin and Huang 2017; Nasar, Hecht, and Wener 2008). Researchers estimated that about 2 million pedestrian injuries were related to cell phone use in 2010 in the United States (Nasar and Troyer 2013). Cell phone use during walking leads to distracted attention, increased cognitive load, and reduced situation awareness (Hatfield and Murphy

2007; Lin and Huang 2017; Nasar, Hecht, and Wener 2008; Neider et al. 2010). With a simulated pedestrian environment, researchers have shown that people distracted by music or texting on a cell phone are more likely to be hit by a vehicle (Schwebel et al. 2012). This is consistent with common observations in real-world scenarios. For instance, during talking or texting on the phone, pedestrians have been observed to have fewer successful road crossings and longer latency to initiate a crossing (Banducci et al. 2016). Thus, cell phone use during walking is regarded as an

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unsafe behaviour which may lead to injury or even casualty.

Using dual-task paradigms, researchers can investigate the influence of cell phone use on walking and assess the deterioration in walking performance due to the demands of dual tasks. There are growing number of studies examining the specific aspects of walking that are affected by cell phone use (Cha et al. 2015; Demura and Uchiyama 2009; Kao et al. 2015; Lamberg and Muratori 2012; Lim et al. 2015, 2017; Parr, Hass, and Tillman 2014). In an early study, researchers observed that the gait speed decreased when a walking participant used the email function of a cell phone (Demura and Uchiyama 2009). Subsequent studies found that many other gait performance measures were also affected by cell phone use, including reduced stride time and double support time, increased step width and stride time variability, and compromised walking stability (Kao et al. 2015; Parr, Hass, and Tillman 2014; Sammy et al. 2015; Schabrun et al. 2014).

With regard to the underlying causes of these gait alternations, previous studies have suggested that increased motor demand, decreased visual information, and increased cognitive load may affect human gait in dual-task scenarios (Agostini et al. 2015; Banducci et al. 2016; Bruijn et al. 2010; Dubost et al. 2006; Hallemans et al. 2010; Kao et al. 2015; Langer et al. 2005; Marone et al. 2014; Pijnappels et al. 2010; Reynolds and Day 2005; Sammy et al. 2015; Schabrun et al. 2014; Yogev et al. 2005). However, there are controversies about which factor is more influential. For example, in one study, researchers suggested that physical demand of texting is a dominating factor influencing walking stability, and the cognitive demand of texting is negligible, while they did not examine the contribution of the visual factor (Marone et al. 2014). In another study, researchers similarly found that different levels of cognitive demands did not lead to significant changes in walking even though texting influenced gait parameters (Sammy et al. 2015). On the contrary, some researchers argued the cognitive demand was the most influential factor affecting walking (Banducci et al. 2016). Interestingly, in their experiment, they lumped together the contribution of visual factor together with that of the cognitive demand and neglected the contribution of a motor factor.

Besides the inconsistency about which factor is the leading contributor to the effect of texting, few studies have examined the relative contributions of these factors. One exception is a study performed by

Marone and colleagues. Besides the two usual conditions of normal walking and texting during walking, they instructed participants to either walk and look at a hand-held cell phone, or walk and verbally report the results of mental calculations (Marone et al. 2014). By comparing to simple walking, these authors argued that the walk-and-look condition involved extra physical/motor demands, while the walk-and-calculation condition involved extra cognitive demands. However, this study only focused on the walking stability in the frontal plane, without measuring and analyzing other commonly used gait performance measures. What's more, the influence of reduced visual information cannot be assessed as limited by the experimental design.

The present study aims to tease out the contributions of the increased motor demand (the motor factor), decreased visual information (the visual factor) and increased cognitive demand (the cognitive factor) to decrement of walking performance caused by texting. We designed four conditions to provide adequate controls for the confounding factors. A digit ordering task (Hoppe et al. 2000) and a finger tapping task were used as the dual tasks to simulate the cognitive demands and the motor demands, respectively. The digit ordering task requires intensive cognitive processing and precise manual operations on the phone. The finger tapping task requires manually holding the phone and tapping on the phone with both thumbs, close to a texting task in terms of motor demands but only with slight cognitive demands. Gait data and digit ordering performance were recorded. By comparing performance between conditions, we quantified the influences of the motor factor, the visual factor and the cognitive factor on gait alternations. The influence of walking on the performance of digit ordering task was also analyzed.

Methods

Participants

Thirty-two young adults were recruited from Peking University (including 21 females; age range 20–27 years). The demographic information and information about cell phone use experiences were collected before the experiment. All participants had used a smartphone for at least 1 year and had experience of cell phone use during walking. Sixteen participants were using iPhone and the other half using Android OS smartphones. Six participants (18.75%) reported that they had experienced small accidents, such as bumping into pedestrians and slipping on the road, at least once when they walked and texted at the same time.

Data collection lasted approximately an hour, and each participant received 40 Yuan (equivalent to about 6 dollars) for their participation. All participants were right-handed, had normal or corrected-to-normal vision without a known history of psychiatric, movement or neurological disorders. The study was approved by the ethics committee of Peking University and was carried out by the approved guidelines. We obtained written consent forms from all participants before formal data collection.

Tasks

Participants walked straight at a comfortable pace for 20 m on an indoor plastic runway (8 m wide) with the walking range marked on the ground with tapes. They were encouraged to walk along a single track which was 1.25 m in width. Participants were verbally reminded to stop the trial once they reached the finishing line. The walking trials were categorised into four conditions: (1) walking only (WalkBase condition, served as a baseline walking condition); (2) walking while performing a simple finger-tapping task on the phone and looking ahead without looking at the phone (WalkTap_{Ahead} condition); (3) walking while performing the finger tapping task on the phone with the eyes fixated on the phone screen (WalkTap_{Screen} condition); (4) walking while performing a digit ordering task on the phone (WalkOrder condition).

In the WalkBase condition, participants simply walked at a comfortable pace with normal arm swings, without a secondary task and without holding a cell phone. In the WalkTap_{Ahead} condition, participants were required to hold the cell phone by two hands in front of the body in a comfortable position, look straight ahead on the road and tap on the phone with both thumbs. The participants were encouraged to hold the cell phone at the same position in the three dual-task conditions. The tapping task itself was casually performed since no text input was involved. Instead, two thumbs tapped on two large buttons (Figure 1(a)). The only requirement was to keep the tapping frequency within the range of 1 ~ 5 Hz. If the tapping frequency fell out of the range, the software would remind the participants to tap quicker or slower by playing a recorded voice ('faster' or 'slower'). The tapping task was performed on a customized Android application specifically programmed for the study. Compared to the WalkBase condition, the WalkTap_{Ahead} condition puts extra motor demands on the participants. It constrained the movements of the two arms to hold the cell phone and demanded finger

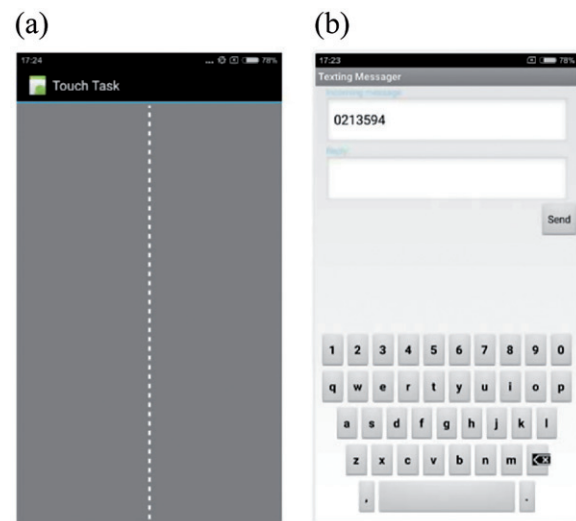


Figure 1. Screenshots of the two cell phone applications used in the experiments. (a) The interface of the finger tapping task. The screen was divided into two halves which served as two tapping buttons for the left and right thumbs, respectively. The central dashed line was not visible to participants. (b) The interface of the digit ordering task. It consisted of two text boxes, the top one was for displaying the random sequence of digits, and the bottom one was for displaying the numbers input by participants.

taps on a cell phone screen in front of the body. We argue that these extra motor demands are similar to the ones involved in texting during walking. The visual and cognitive demands were relatively low in this condition since participants could look straight ahead and the tapping task itself was with little cognitive load. Thus, we attribute the performance difference between WalkTap_{Ahead} and WalkBase conditions mainly to the deteriorating effect of the motor factor.

The WalkTap_{Screen} condition was similar to the WalkTap_{Ahead} condition, except that participants were required to fixate on the phone screen instead of looking straight ahead on the road. Hence, the WalkTap_{Screen} condition puts extra demands on the visual aspect of the task, requiring the participants to shift the fixation from the road to the cell phone screen. The experimenter closely monitored participants' behaviours during the experiment and ensured that the subjects followed the instruction during the experiment. This reduction of visual information from the central visual field would worsen their walking performance, which is attributed to the deteriorating effect of the visual factor.

In the WalkOrder condition, participants were required to perform a digit ordering task on a cell phone while walking (Hoppe et al. 2000). On the screen of the cell phone, a sequence of 7 single-digit numbers was presented in a random order

(Figure 1(b)). The participants needed to type in these digits in ascending order with a typical Android system keyboard (QWERTY) and then pressed a 'send' key. Participants were allowed to correct for any input error by using the backspace button before pressing the 'send' button. After the digits were sent, a new digit ordering trial would begin by showing a new random sequence of digits if the participant had not walked for 20m. The instruction for the digit ordering task emphasised both speed and accuracy. The task was performed on a customised Android application which recorded all finger inputs during the experiment for offline analyses (He et al. 2014). The task was used to simulate the typical performance of texting since both tasks shared common cognitive processes such as attention sustaining, working memory and error monitoring, etc. Importantly, the WalkTap_{Screen} condition and the WalkOrder condition shared similar visual and motor demands as both conditions required participants to hold the cell phone by two hands, fixate on the cell phone screen, and tap on the screen with a similar tapping rate. The critical difference between these two conditions was that the WalkOrder condition had extra demands on cognitive processes since digital ordering is more cognitively challenging than casual tapping. The performance difference between the WalkTap_{Screen} condition and the WalkOrder condition was thus attributed to the effect of the cognitive factor.

The above four walking conditions were tested in separate blocks, with six trials in each block. The order of these blocks was counterbalanced across participants.

Participants also performed a baseline digit ordering task during still standing (OrderBase condition), in which task participants simply performed 10 trials of digit ordering task without walking.

Equipment

The cell phone used in the present study was a RedMi Note2 (capacitive touchscreen, screen size: 5.5 inches, resolution: 1920 × 1080 pixels; Xiaomi Inc., Beijing, China). It was held in front of the participant by both hands. Participants also wore an inertial-based full-body motion capture system during walking (Perception Neuron, Noitom, Beijing, China). There were 17 inertial markers placed on the participant's trunk and limbs. The sampling rate of the motion capture was 125 Hz. Theoretically, the motion capture system can estimate the position of each sensor in extrinsically defined coordinates system with the aid of a body configuration

model. In our experiment, only the displacement data of the foot and pelvis were analysed.

Measures and analyses

Among the many gait parameters, four parameters were selected, including gait speed, stride length, stride time and stride time variability. The four parameters were selected for two reasons. Firstly, they were commonly used parameters for characterising the spatiotemporal changes in gait during dual tasks (Agostini et al. 2015; Demura and Uchiyama 2009; Dubost et al. 2006; Sammy et al. 2015). Secondly, they can be calculated reliably from the raw measures from our motion capture system. Gait speed was defined as the mean speed of pelvis in the walking direction. To remove transient effects at the beginning and the ending of walking, data of the first and the last two meters were excluded for calculation of gait speed. Stride length was the average distance travelled by a foot between consecutive heel strikes. Stride time was the time between consecutive heel strikes. Stride time variability was defined as the coefficient of variation (CV) of stride time within a trial according to Equation (1).

$$CV = \frac{\text{standard deviation (stride time)}}{\text{mean (stride time)}} \times 100\% \quad (1)$$

Task cost (TC) was defined as the decrement of performance in a difficult condition relative to an easy condition (Hamilton et al. 2009). It was calculated as a percentage of performance change (Equation 2) where *Difficult Condition* represents a performance measure in a relatively difficult condition, and *Easy Condition* represents the same performance measure in a relatively easy condition.

$$TC = \frac{|\text{Difficult Condition} - \text{Easy Condition}|}{\text{Easy Condition}} \times 100\% \quad (2)$$

Importantly, using Equation (2), we computed TCs of the motor factor, the visual factor and the cognitive factor by defining their corresponding *Easy Condition* and *Difficult Condition* (Table 1). Of note, we estimated four measures of gait performance, i.e. gait speed, stride length, stride time and stride time variability. Thus, TC for each factor could be estimated based on these four gait measures.

Table 1. The setting of conditions for task cost calculation.

	Easy condition	Difficult condition
Motor factor	WalkBase	WalkTap _{Ahead}
Visual factor	WalkTap _{Ahead}	WalkTap _{Screen}
Cognitive factor	WalkTap _{Screen}	WalkOrder

We also evaluated the performance of the digit ordering task, and compared subjects' performance of the digit ordering task in the WalkOrder condition with that in the OrderBase condition. The speed of performance was quantified by average typing interval. The accuracy of performance was evaluated by quantifying how similar the ordered number sequence was to the correct sequence. Effectively, this measure is the minimum number of operations required to transform one string sequence into the other, and it is termed as edit distance in computer science (He et al. 2014; Levenshtein 1966). The increase of key presses, defined as the percentage increase of the number of actual key presses compared to the number of key presses that was minimally needed, was computed as another measure of ordering errors occurred in each trial.

Data analyses were performed by custom MATLAB scripts (MathWorks, Natick, MA, USA) and Python scripts. The statistical analyses were performed using SPSS 20.0 (IBM Corp., New York, NY, USA). MANOVA tests were performed to compare multivariate sample means when there were two or more dependent gait parameters. Univariate repeated-measures ANOVAs were used to test whether there were significant condition differences for each gait parameter. If an ANOVA test obtained a significant omnibus test result, *post-hoc* pair-wise comparisons were conducted with Fisher's LSD method to determine which means were different. The TC of each factor was also tested against zero by a one-sample *t*-test to detect any significant influence of that factor on gait. Paired *t*-tests were performed to compare the ordering performance in the WalkOrder condition and the OrderBase condition. The significance level was set at $\alpha = 0.05$.

Results

Gait performance measures

Comparisons of gait performance measures between the four walking conditions

Correlation analyses showed that three gait measures, i.e. gait speed, stride time and stride length, were highly correlated. For example, in the WalkOrder condition, gait speed was positively correlated with stride length ($r = 0.839$, $p < .001$), and negatively correlated with stride time ($r = -.760$, $p < .001$). However, there was no significant correlation between stride time variability and other measures ($r = -0.034$, -0.108 , -0.125 , $p = .853$, $.555$, $.496$, for correlation with gait speed, stride length and stride time, respectively).

Thus, a one-way MANOVA was performed on the three correlated gait measures (gait speed, stride length, stride time), which yielded a significant multivariate main effect for walking condition, Wilks' $\lambda = .537$, $F(9, 290.067) = 9.604$, $p < .001$. Given the significance of the overall test, univariate ANOVAs were performed, and found significant condition differences in all four gait performance measures (with significant results on Mauchly's Test of Sphericity, gait speed: $F(1.61, 49.91) = 138.96$, $p < .001$, $\eta^2 = 0.74$; stride length: $F(1.72, 53.42) = 164.76$, $p < .001$, $\eta^2 = 0.76$, stride time: $F(2.15, 66.59) = 155.36$, $p < .001$, $\eta^2 = 0.70$; stride time variability: $F(2.44, 75.72) = 34.05$, $p < .001$, $\eta^2 = 0.31$).

Post-hoc pairwise comparisons showed that gait performance deteriorated in the three dual-task conditions when compared with the WalkBase condition (gait speed: $p < .001$, $p < .001$, $p < .001$ for WalkTap_{Ahead}, WalkTap_{Screen}, and WalkOrder conditions, respectively; stride length: $p < .001$, $p < .001$, $p < .001$ for WalkTap_{Ahead}, WalkTap_{Screen}, and WalkOrder conditions, respectively; stride time: $p < .01$, $p < .001$, $p < .001$ for WalkTap_{Ahead}, WalkTap_{Screen}, and WalkOrder conditions, respectively; stride time variability: $p < .05$, $p < .01$, $p < .001$ for WalkTap_{Ahead}, WalkTap_{Screen}, and WalkOrder conditions, respectively). Specifically, people walked slower with smaller stride length and larger stride time variability in all these dual tasks.

Post-hoc comparisons also found that, among the three dual-task conditions, generally, the WalkTap_{Ahead} condition had significantly better performance than the WalkTap_{Screen} condition and WalkOrder condition; and the WalkTap_{Screen} condition had significantly better performance than the WalkOrder condition (Figure 2).

Comparisons of TCs of the motor, visual and cognitive factors

By evaluating the difference between conditions, we quantified TCs of the three factors affecting gait. For gait speed, TCs (mean $\pm$ SE, same below) were $10.8\% \pm 1.7\%$, $5.8\% \pm 0.7\%$, and $17.9\% \pm 1.4\%$ for the motor factor, visual factor, and cognitive factor, respectively. For stride length, TCs were $6.6\% \pm 1.1\%$, $3.8\% \pm 0.4\%$, and $9.1\% \pm 0.7\%$ for the motor factor, visual factor, and cognitive factor, respectively. For stride time, TCs were $6.1\% \pm 1.0\%$, $3.3\% \pm 0.4\%$, $10.0\% \pm 0.9\%$ for the motor factor, visual factor, and cognitive factor, respectively. For Stride time variability, TCs were $22.2\% \pm 3.9\%$, $12.2\% \pm 1.6\%$, $25.4\% \pm 3.4\%$ for the motor factor, visual factor, and cognitive factor, respectively. One-sample *t*-tests showed that all TCs were significantly higher than zero ($p < .001$ for all

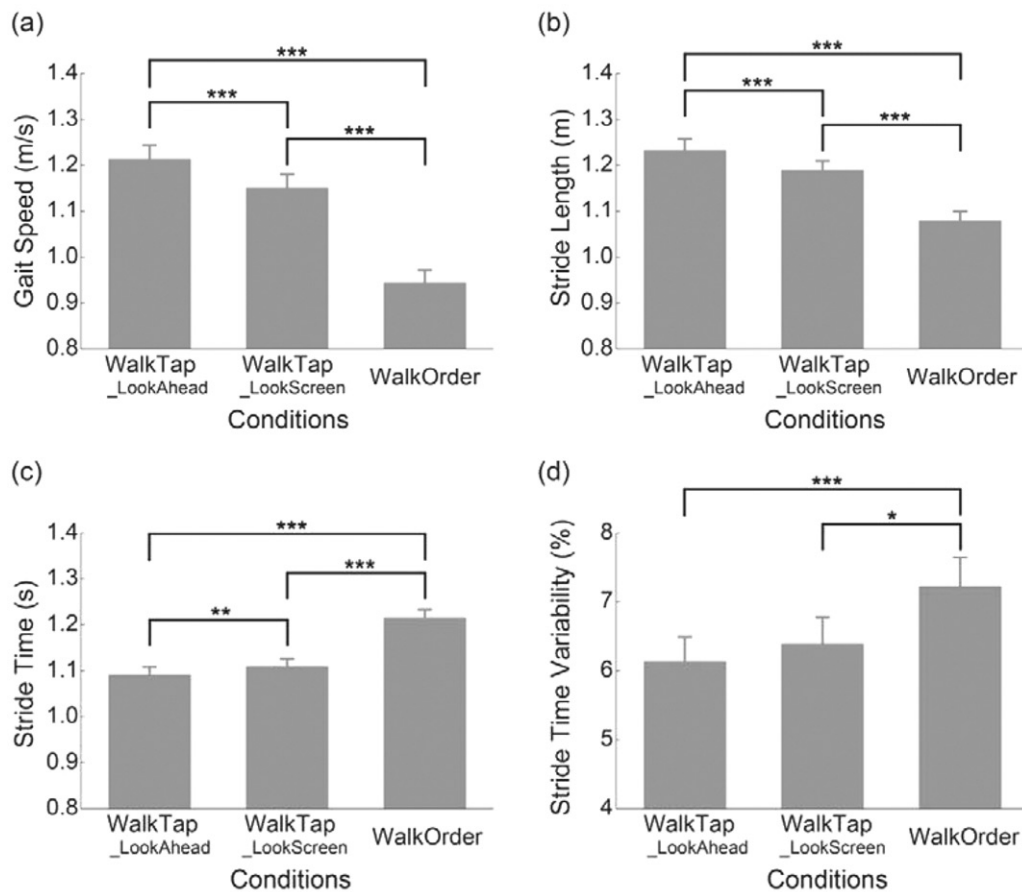


Figure 2. Comparisons of gait performance measures in the dual-task conditions. Gait performance measures include gait speed (a), stride length (b), stride time (c) and stride time variability (d). *** $p < .001$. ** $p < .01$. * $p < .05$.

cases), indicating that the motor factor, the visual factor and the cognitive factor all contribute significantly to gait alternations.

We then compared three factors using repeated-measures ANOVA and found that they were significantly different no matter which gait measures were used (gait speed: $F(2, 62) = 21.69$, $p < .001$, $\eta^2 = 0.41$); stride length: $F(2, 62) = 11.10$, $p < .001$, $\eta^2 = 0.26$); stride time: $F(2, 62) = 17.40$, $p < .001$, $\eta^2 = 0.36$; stride time variability: $F(1.53, 47.38) = 4.42$, $p < .05$, $\eta^2 = 0.12$, with a significant Mauchly's Test of Sphericity for Stride time variability). Post-hoc pairwise comparisons found that generally for the four gait performance measures, the cognitive factor had higher TC than the motor factor and the visual factor; the motor factor had higher TC than the visual factor (Figure 3). Thus, we conclude that comparisons between the three factors yielded a rank order of contributions: the cognitive factor contributed the most to gait alternations, the visual factor the least, and the motor factor in between. Correlation analyses showed that there was no significant correlation between TC of motor factor, TC of visual factor, and TC of cognitive factor across

all the four gait measures. Thus, the fact that the ordering of TC remained relatively stable across all the four gait measures suggests that the relative contributions of the motor, visual and cognitive factors to gait alternations were reliably estimated.

Performance of the digit ordering task

The performance of the digit ordering task was found to be affected by walking (Figure 4). Performance of the digit ordering task in the WalkOrder condition and the OrderBase condition was compared by paired t -tests. The typing time interval was significantly larger in the walking condition compared to the baseline condition (WalkOrder: 2.17 ± 0.10 s, OrderBase: 1.32 ± 0.10 s, $t(31) = 7.61$, $p < .001$). There was no significant difference in edit distance between these two conditions (WalkOrder: 0.66 ± 0.10 , OrderBase: 0.60 ± 0.10 , $t(31) = 0.46$, $p = .65$). There were higher error rates of key presses during walking as demonstrated by an increased number of key presses (WalkOrder: $17.21\% \pm 2.46\%$, OrderBase: $11.27\% \pm 1.65\%$, $t(31) = 2.04$, $p = .05$). Taken together, these results indicate that performance of the digit

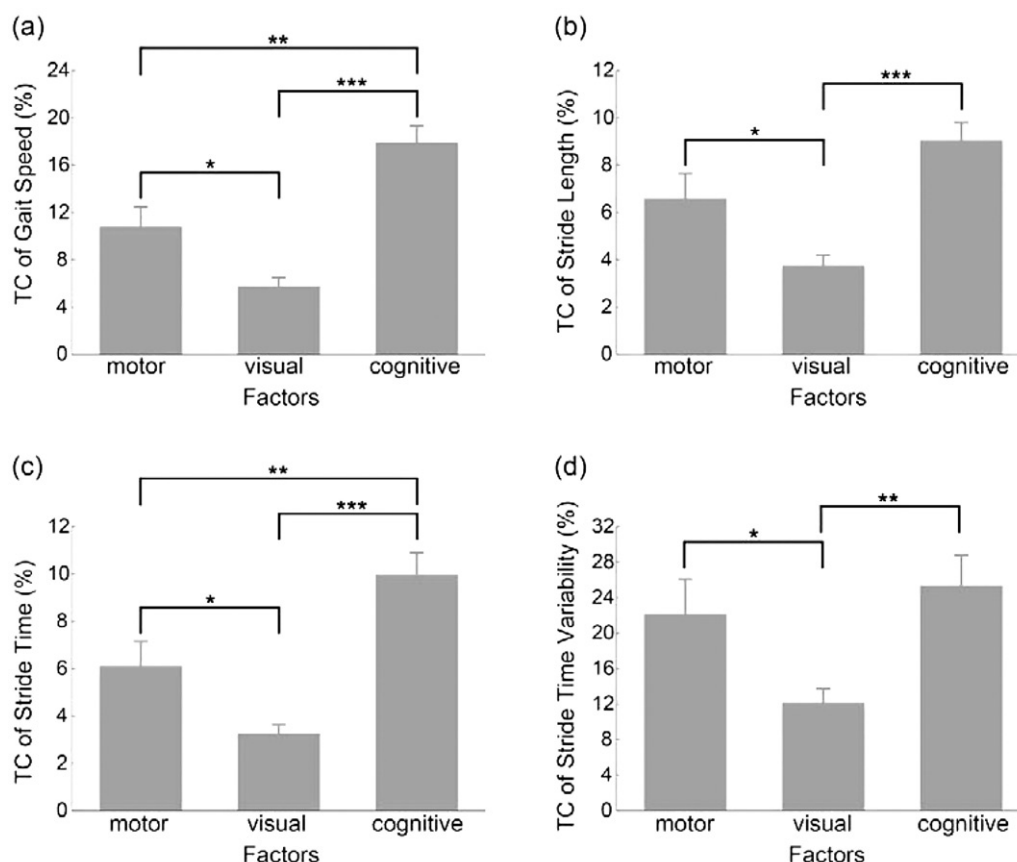


Figure 3. Task cost (mean $\pm$ SE) of motor, visual and cognitive factors. Costs based on gait speed (a), stride length (b), stride time (c) and stride time variability (d) are shown separately. TC: task cost. *** $p < .001$. ** $p < .01$. * $p < .05$.

ordering task was significantly worse during walking as compared to during still standing.

Discussions

The current study aims to quantify the contributions of the motor, visual and cognitive factors to performance decrement in walking when a manual task such as texting is performed on a hand-held cell phone. Comparing multiple experimental conditions, we find that all these factors have significant impacts on various gait performance measures. Specifically, these factors cause a decrease in gait speed and stride length, and an increase in stride time and stride time variability. In our experiment, a digit ordering task is used to simulate texting, and in this case, the cognitive factor contributes the most to gait alternations, the visual factor the least, and the motor factor in between.

Influence of the motor factor on gait

Texting while walking causes two major changes to motor control of walking. The first change is that movements of one or two arms are constrained due to the need to hold the cell phone in front of the

user. The second change is that fingers need to tap on the phone. Arguably, our WalkTap_{Ahead} condition simulates the two motor changes while it minimises the cognitive and visual demands during the dual task. By comparing gait performance in the WalkTap_{Ahead} condition and the WalkBase condition, we demonstrate that the motor factor indeed has a significant influence on gait, to the extent that is even larger than that of the visual factor.

Previous studies have looked into the influence of the motor factor (or called physical demand) induced by cell phone use on gait (Marone et al. 2014; Kao et al. 2015), but its effect has often been confounded with effects of the visual factor or/and the cognitive factor. For instance, a recent study has similarly found significant differences between the single task of walking and dual tasks of operating on a phone during walking (Kao et al. 2015). The authors concluded that the added physical demand might cause gait modifications. However, compared to the walking only condition, the dual-task tasks required participants to hold and look at something in their hands, which arguably increased not only physical demand but also visual and cognitive demands. Another recent study tried to

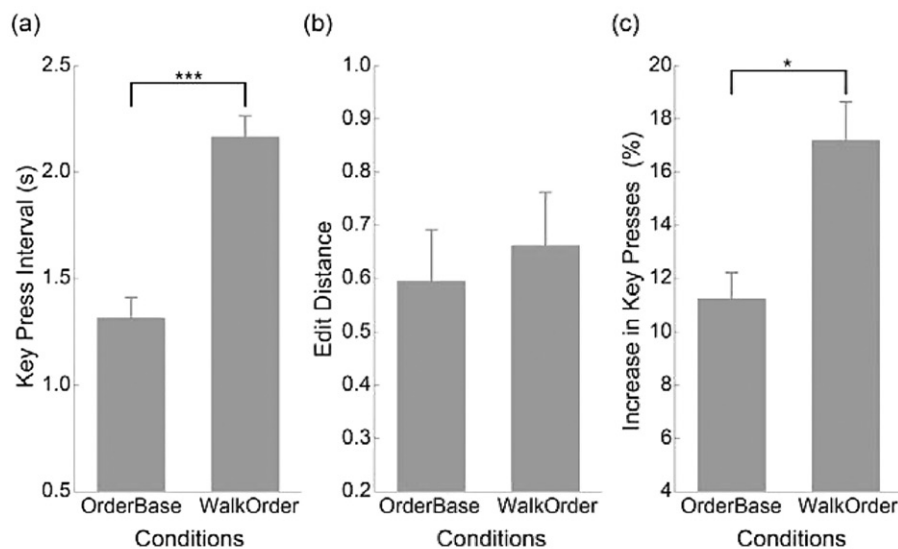


Figure 4. Performance of the digit ordering task in the still standing condition (the OrderBase condition) and walking condition (the WalkOrder condition). The performance indices are the time interval between key presses (a), edit distance (b), and the increase in key presses (c). *** $p < .001$. * $p < .05$.

remove the confounds by comparing a normal walking condition and a dual-task condition that required the walking participants to bimanually hold and look directly at a phone (Marone et al. 2014). These authors found that walking stability was reduced in the dual-task condition and concluded that this effect was due to physical demand. We would argue that this further endeavour did not remove the confounds completely: similar to our WalkTap_{Screen}, their decrement in walking performance in the dual task may be partially caused by reduced visual inputs. Our WalkTap_{Ahead} condition was designed to resolve the confounding role of the visual factor by asking participants to look straight ahead, just as they did in the single task of walking. This more elaborate design of experimental conditions, in the end, indicate that the motor cost indeed plays an important role even when the influences of other factors are minimised.

Some researchers attempted to directly address the effect of the limitation of arm swing on gait by strapping one or both arms of the participants (Eke-Okoro, Gregoric, and Larsson 1997). They found that, compared to normal walking, constraining the movements of one or two arms resulted in a decrease in stride length, stride frequency, and walking speed. However, though strapping one or two arms to the body can limit the arm swing, it is still very different from the actual texting movements which requires to hold a cell phone and operate on its screen. Tapping on the phone requires the motor system to dynamically coordinate the movements of the arms and fingers

with those of the lower limbs. In fact, strapping arms on the trunk side lead to a distinct walking pattern from normal walking and walking with concurrent phone use. We argue that compared to strapping arms during walking, our walking and tapping tasks have more ecological validity for simulating typical dual task of texting during walking. Future studies can use a condition that requires subjects to walk while holding the phone without tapping to evaluate the influence of finger tapping on gait performance while separating the influence of constraining the arms.

Influence of the visual factor on gait

In our study, the visual factor has a significant influence on gait performance measures, confirming the contribution of central vision to walking (Timmis and Shahina 2012; Timmis et al. 2014; Timmis, Scarfe, and Pardhan 2016). The influence of the visual factor was shown by the significant differences in walking performance between the WalkTap_{Screen} condition and the WalkTap_{Ahead} condition. Texting on a cell phone requires visual fixation on the phone thus the central visual field is continuously occupied, resulting in the reduced visual information of the surroundings. However, compared with the cognitive factor and the motor factor, the contribution of the visual factor is relatively small. This is not surprising given that both the central and peripheral vision can be used to support posture during walking (Bardy, Warren, and Kay 1999), and patients with central vision loss showed

normal performance in the walking-only task in the laboratory (Timmis and Shahina 2012). We postulate that in our experiments, the relatively unaffected peripheral vision may compensate for the negative impact of the reduction of central vision. In fact, this postulation is indirectly supported by the finding that stride time variability was not significantly different between the WalkTap_{Ahead} condition and the WalkTap_{Screen} condition, which reflected that the impact of lack of central vision to walking stability is limited when participants fixated on the phone. Meanwhile, the gait speed and stride length decreases and the stride time increases, possibly due to the fact that the walkers took a more conservative strategy with the loss or occlusion of the central vision, similar to patients with loss of central visual field (Timmis and Shahina 2012; Timmis, Scarfe, and Pardhan 2016). Of note, we do not argue that peripheral vision is not affected by our dual tasks; people have found that cell phone use also reduces visual inputs from the peripheral vision (Langer et al. 2005). What has not been explored, either in the literature or by the present study, is how the specific location of the held phone would affect the visual inputs and subsequently the gait. People could hold the phone at different heights and distances away from the body. We believe that visual inputs and gait performance will be more compromised if more head bending is involved. This warrants further investigations. In our controlled experimental environment, the participants were free from potential hazards, such as obstacles, dangerous terrains or traffic; this may also alleviate the negative impact of the visual factor.

In our experiment, the participants were instructed to look ahead on the road in the WalkTap_{Ahead} condition, and look at the phone screen in the WalkTap_{Screen} condition. As the experimenter observed and enforced, the participants successfully followed the instructions. However, an eye tracking system (such as a glass-shape eye tracker) is recommended to be used for future studies to automatically monitor participants' gazes.

Influence of the cognitive factor on gait

Cell phone use during walking increases the cognitive workload of the walker in many aspects, among which attention, memory, and executive control are commonly mentioned (Lim et al. 2015; Springer et al. 2006; Yogev, Hausdorff, and Giladi 2008). In the current study, the WalkOrder condition and the WalkTap_{Screen} condition are compared to demonstrate

the effect of the cognitive demand during actual texting. Compared to the WalkTap_{Screen} condition, the WalkOrder condition put more demands on various cognitive processes including visual attention, working memory, and executive control. We find that these higher cognitive demands indeed lead to a poorer walking performance in the WalkOrder condition than that in the WalkTap_{Screen} condition. In fact, our results showed that the cognitive factor had the strongest impact on gait performance among the three factors considered in this research.

The strong influence of cognitive factor on human gait is generally in line with many previous studies (Banducci et al. 2016; Lamberg and Muratori 2012; Sammy et al. 2015). Interestingly, some previous studies have reported that the influence of cognitive demand on healthy adults' gait was small (Marone et al. 2014; Springer et al. 2006). The discrepancy is very likely due to the characteristics of the dual tasks used. Reading and texting as the dual task of walking usually bring significant changes to gait performance (Banducci et al. 2016; Lamberg and Muratori 2012; Sammy et al. 2015), while tasks with auditory input or/and verbal responses tend to bring relatively small alternations in gait (Marone et al. 2014; Springer et al. 2006). Direct comparisons of the interference of texting and talking to walking have revealed that texting on a cell phone usually caused greater influence to walking performance than talking on a cell phone (Banducci et al. 2016; Lamberg and Muratori 2012). Interestingly, some researchers identified considerable visuospatial processing demands for normal walking (Marianna, Paolo, and Hausdorff 2013). We postulate that the texting task and its variants require visual attention, visually-mediated motor control, and processing of visual items on the screen. Thus, this kind of phone use tasks might compete with walking in terms of spatial processing resources, resulting in large interference effects. In contrast, talking on the phone or verbally responding to auditory stimuli might have fewer demands on spatial processing and thus less interference with walking (Wickens 2008).

The importance of cognitive load during walking has also been shown in studies on ageing. For example, many previous studies have shown that elderly people walked with slower speed and decreased stability than young people, which have been attributed to ageing-related decrement of cognitive functions (Li et al. 2001; Li, Verghese, and Holtzer 2014; Lindenberger, Marsiske, and Baltes 2000; Schaefer and Schumacher 2011; Springer et al. 2006; Yogev, Hausdorff, and Giladi 2008). We believe that the

interference of texting to walking would be more severe if our experiments were carried out among the elderly.

We have shown that the cognitive factor contributes more to gait alternations than the motor factor and the visual factor. However, this ranking order of importance might not hold across different participant groups and different phone-use tasks. After all, we have to take into consideration the individual differences in cognitive functions and the task differences in terms of cognitive demands for different phone use tasks. However, our study demonstrates that for a difficult task like digit ordering, the cognitive factor is most influential in affecting gait performance.

Influence of walking on the dual task on the phone

The performance of the digit ordering task was found to be negatively affected by walking, which is consistent with previous studies on various dual tasks performed during walking (Lim et al. 2015; Simoni et al. 2013; Yogev, Hausdorff, and Giladi 2008). We found that both the speed and the accuracy of the digit ordering task performed on the cell phone decreased significantly in the WalkOrder condition compared to the OrderBase condition. This phenomenon confirms that the walking task also demands on cognitive resources (Marianna, Paolo, and Hausdorff 2013), thus interferes with the performance of the dual task.

Implications and limitations

The current research found that the motor, visual and cognitive factors, which are involved in texting on a cell phone, all have significant impacts on the gait performance among normal young adults. We further hypothesise that the elderly would exhibit more decrement in walking performance if texting while walking. The decrement in gait performance such as gait speed and stride length is not necessarily an indicator of poor gait control, but rather an adapted coordination pattern to reduce the risk of accident (i.e. bumping into people or obstacles) and to enable completion of the dual task. However, considering the increasing number of accidents and injuries associated with phone use, we still recommend avoiding texting or similar phone use behaviours during walking, especially for the elderly. When one has to reply to a message or send a message on the phone by texting, standing at a safe place to perform texting may be a wise choice. A potential approach to reducing the

cognitive and motor costs is to increase the size of keys to lower spatial processing demands and motor demands. An adjustable keyboard that can automatically recognise a walking phone user and adaptively change its size might be desired to alleviate the negative impact of texting on walking. A better choice is to reply the message by voice recording or voice-to-text translation. This will spare the cost of the visual factor, leading to smaller interference to walking than that of texting on the phone.

Our study has at least two limitations. First, we have evaluated four gait performance measures, but other gait variables are left unchecked, including trunk stability, gait symmetry, head stability, and coordination between limbs. In future studies, these gait measures may be investigated to obtain a more comprehensive understanding of the influence of texting on walking. Second, our experiments were carried out on an indoor plastic runway, which was much safer than the actual street walking environment. Future studies shall investigate related problems in street environments to increase the ecological validity of the research.

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