



Cerebral cortical networking for mental workload assessment under various demands during dual-task walking

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Abstract

While several studies have examined attentional reserve (via event-related potentials) and mental effort (via EEG spectral content) from various cortical regions during dual-task walking, none have assessed changes in the magnitude of interregional (cortico-cortical) communication as a measure of mental workload. Therefore, by deploying a traditional montage of electrode sites centered over the motor planning region as well as a more comprehensive graph theory-based approach encompassing the entire scalp, this study aimed to systematically examine changes in the magnitude of functional connectivity underlying cortico-cortical communication to assess changes in mental workload under various levels of challenge. Specifically, the Weighted Phase Lag Index (WPLI) was computed to assess the changes in magnitude of functional connectivity as participants performed a cognitive task under two demands (low and high) and two conditions (seated and walking). The results revealed enhanced fronto-centro-temporo-parietal theta connectivity during dual-task walking relative to being seated as well as a reduced inhibition of fronto-centro-temporo-parieto-occipital alpha networking as the demand on the secondary cognitive task increased. Collectively, these findings may reflect greater recruitment of task relevant processes to respond to increased cognitive–motor demands and thus an elevation of mental workload in an effort to maintain performance under varying levels of challenge. This work has the potential to inform future mental workload assessment applications in patient populations, including those who employ prostheses during cognitive–motor performance under various task demands.

Keywords Mental workload · EEG functional connectivity · Dual-task walking · Theta networking · Alpha connectivity

Introduction

High-quality cognitive–motor performance is largely dependent on the efficient allocation of limited cognitive–motor resources to respond to the corresponding task demands. When faced with excessive demands, cognitive–motor resources are further recruited, as reflected by an

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increased mental workload, in an attempt to maintain performance and respond to the challenge in an effective manner (Gentili et al. 2018; Gevins and Smith 2003; Rietschel et al. 2012; Shaw et al. 2018; Wickens 2002, 2005, 2008). Mental workload is defined here as a multidimensional concept corresponding to the resources which can be recruited (e.g., attention, working memory, motor coordination, sensory/sensorimotor integration) by the performer to successfully respond to essential task demands in order to perform appropriately (Hancock and Warm 1989; Wickens 2002, 2005, 2008; Young et al. 2015). If the resources recruited exceed a threshold of tolerance, then critical cognitive–motor processes underlying behavior are compromised, resulting in performance decrements and/or an inability to attend to additional and, possibly, unexpected task demands (Alderman et al. 2014, 2015; Berka et al. 2007; de la Peña et al. 2008; Murray and Janelle 2007; Murray and Russoniello 2012; Olson et al. 2016; Rietschel et al. 2012; Wickens et al. 1983).

The study of mental workload is informative to optimization (e.g., neuroergonomics; Berka et al. 2007; Parasuraman and Wilson 2008) and rehabilitation (e.g., patient rehabilitation; Deeny et al. 2014) of human performance and may provide insight into relevant neural processes underlying the quality of cognitive–motor behavior. In particular, mental workload assessment during dual-task walking has recently received considerable attention due to the essential role locomotion plays in everyday functioning. The majority of this work, however, has relied heavily on the evaluation of behavior, such as gait biomechanics and cognitive task performance, in order to infer the cognitive–motor demands imposed on individuals as they dual-task walk (Dubost et al. 2006; Hollman et al. 2007; Morgan et al. 2016, 2017). Although informative, behavioral analyses do not fully reflect the cognitive–motor processes required to successfully perform a task. Examination of brain dynamics during walking and the performance of a secondary task offer additional insight beyond behavioral measures, allowing for a robust assessment of mental workload.

One approach to examine changes in brain dynamics related to modulations in mental workload during cognitive–motor performance is to employ electroencephalography (EEG). In particular, component amplitudes of the event-related potential (ERP) waveform and EEG spectral content can serve as robust indices of the changes in resource allocation related to attention and cognitive–motor processes during walking and the concurrent performance of a secondary task of varying levels of challenge (Beurskens et al. 2016; De Sanctis et al. 2014; Malcolm et al. 2015; Marcar et al. 2014; Shaw et al. 2018; Yokota et al. 2017). Such analyses are limited, however, as they focus on local modulations in cortical activity recorded from specific regions and not on the changes in interregional connectivity

(i.e., cerebral cortico-cortical communication). The assessment of EEG spectral power and ERP components poses a limitation because they are indicative of regional activity, whereas it is well accepted that brain processes are achieved through distributed interconnected regions, resulting in complex neural network interactions (Laughlin and Sejnowski 2003; Sporns et al. 2005). For instance, attentional control and working memory are dependent on the fronto-parietal network and are not localized to one specific cortical region. The present study assessed changes in the magnitude of cortico-cortical communication to examine the cognitive–motor mechanisms underlying mental workload during dual-task walking and extended previous efforts which focused solely on the modulation of regional cortical dynamics (Shaw et al. 2018; Pruziner et al. 2019).

When considering previous investigations, cerebral cortical networking analyses have been employed to assess cortical dynamics as a function of the level of performance and/or learning. This body of work has demonstrated that changes in theta and alpha functional connectivity between frontal and posterior cortical regions reflect the modulation of various processes such as inhibition, planning, sensory/sensorimotor integration, attention, and working memory (e.g., Cavanagh and Frank 2014; Corbetta et al. 2014; Deeny et al. 2003, 2009; Fries 2005; Gentili et al. 2015; Haibach et al. 2008; Harper et al. 2017; Rietschel et al. 2012; Sauseng et al. 2005; Slobounov et al. 2006; Teel et al. 2014; Wang et al. 2016). More specifically, the examination of motor control and learning mechanisms in various populations has revealed that attenuated theta and low/high-alpha functional connectivity between frontal and other regions is indicative of efficient cognitive–motor processes during task performance, reflecting the level of motor skill acquired by individuals (e.g., Bell and Fox 1996; Busk and Galbraith 1975; Corbetta et al. 2014; Cheng et al. 2017; Deeny et al. 2003, 2009; Gentili et al. 2015; Ghasemian et al. 2017; Haibach et al. 2008; Rietschel et al. 2012; Slobounov et al. 2006; Teel et al. 2014). Relatively few studies have evaluated changes in the magnitude of cerebral cortical connectivity to assess mental workload while manipulating the level of cognitive–motor challenge (Rietschel et al. 2012; Sauseng et al. 2007; Serrien et al. 2004, 2009). The results of the research conducted to date revealed that elevated cognitive–motor demands result in increased cortico-cortical communication between various cortical regions, as reflected by a modulation in EEG theta and alpha coherence, which may be indicative of an attempt to maintain motor performance when faced with greater demands. For instance, Rietschel et al. observed that elevated cognitive–motor demands led to increased theta and low/high-alpha functional connectivity between the motor planning and various non-motor regions (Rietschel et al. 2012). Conversely, other investigations have revealed that increases in cognitive task demands result in

decreased functional connectivity involving the frontal regions, as measured by EEG alpha coherence. Since alpha oscillations have been linked to inhibitory processes, the findings from these studies suggest that there was a strategic cortical disinhibition of neural mechanisms to facilitate engagement of relevant brain processes to overcome elevated demands (Doesburg et al. 2009; Dai et al. 2017; Nikolov 2013; Sauseng et al. 2005; Siegel et al. 2008). By increasing the demand on central executive processes, Sauseng et al. observed a reduction of high-alpha connectivity within the frontal region, which was interpreted as a task-specific attenuation of cortical inhibition in response to the elevated demands on working memory (Sauseng et al. 2005). While these previous efforts provide converging evidence that cortical networking is altered by cognitive–motor task demands, this work was mainly conducted in the context of: (1) cognitive–motor performance without considering a specific evaluation of the changes in mental workload, (2) pure cognitive task performance without incorporating a significant motor component, and/or (3) upper but not lower-extremity performance such as dual-task walking.

The aim of this study was to evaluate whether the magnitude of cortical networking could serve as an index of mental workload during dual-task walking. While locomotion has often been considered as a fully automatic process, controlled by subcortical mechanisms, recent evidence suggests multiple cortical regions are involved (e.g., prefrontal, premotor, parietal regions) during dual-task walking (Artoni et al. 2017; Beurskens et al. 2016; Mirelman et al. 2014; Shaw et al. 2018). Consistent with this notion, changes in the magnitude of cortico-cortical communication between frontal (executive function/motor planning) and other cortical regions implicated in motor, sensory and cognitive mechanisms were evaluated in the current study as individuals performed a secondary cognitive task under various levels of challenge (i.e., low and high demands) while seated or walking. Specifically, mental workload was expected to increase as individuals walked relative to being seated and as the level of difficulty of a secondary task increased (i.e., low vs. high). This elevated level of mental workload was expected to increase the magnitude of theta and alpha connectivity between the frontal (executive/motor planning) and other regions (motor, sensory and cognitive), which would be reflective of an enhanced recruitment of cognitive–motor processes in an effort to maintain successful performance under higher demands. Although the results of previous studies suggest that dual-task walking involves cortical control (including the motor/premotor regions), it is uncertain if a traditional electrode montage centered at the motor planning region (i.e., centered at Fz), which has been commonly employed to assess mental workload during upper-extremity performance, is sensitive enough to capture the cortical networking dynamics during dual-task walking.

Thus, a secondary analysis employing graph theory was employed, in addition to a conventional topographic assessment, which considered the entire scalp to identify a topology of networks to determine if connectivity was altered based on varying cognitive–motor demands. The secondary analysis allowed for the examination of detailed cortical networking patterns underlying any observed changes in mental workload.

Methods

Participants

Fifteen healthy individuals were enrolled in this study. Upon removal of one participant due to technical issues, the final sample consisted of fourteen individuals (13 men and 1 woman; age range 21–35 years). All participants reported no history of neurological impairment, were not taking medication known to alter the central nervous system, had normal or corrected-to-normal vision and were free of drug and alcohol use at the time of participation (confirmed by a urine drug test and breathalyzer, respectively). Additionally, all participants reported feeling comfortable while walking on a treadmill and reported no previous injuries or illnesses that affect gait and balance. Written informed consent, approved by the institutional review board at Walter Reed National Military Medical Center (WRNMMC), was provided by all individuals prior to participation. The variables presented in the next sections (i.e., cortical networking, cognitive performance and National Aeronautics and Space Administration-Task Load Index (NASA-TLX) surveys) are derived from the re-analysis of a data set examined in two previous studies (Shaw et al. 2018; Pruziner et al. 2019).¹

Experimental protocol

Participants were instructed to complete a concurrent task under two levels of cognitive demand² (low and high) both

¹ This secondary analysis was conducted in the context of a larger effort for which the relevant biomechanics were already reported in Pruziner et al. (2019), revealing that uninjured individuals did not exhibit any changes in walking dynamics (e.g., mean stride width and double support; stride width and double support variability) in the high relative to the low cognitive task demand.

² In the remainder of the manuscript, the cognitive and cognitive-motor demands refer to the demands related to the secondary cognitive task and dual-task walking, respectively. Similarly, the cognitive and cognitive-motor resources (e.g., attention, working memory, motor coordination, sensory/sensorimotor integration) recruited by the participants to respond to the corresponding demands are those involved in the secondary cognitive task and the dual-task walking, respectively.

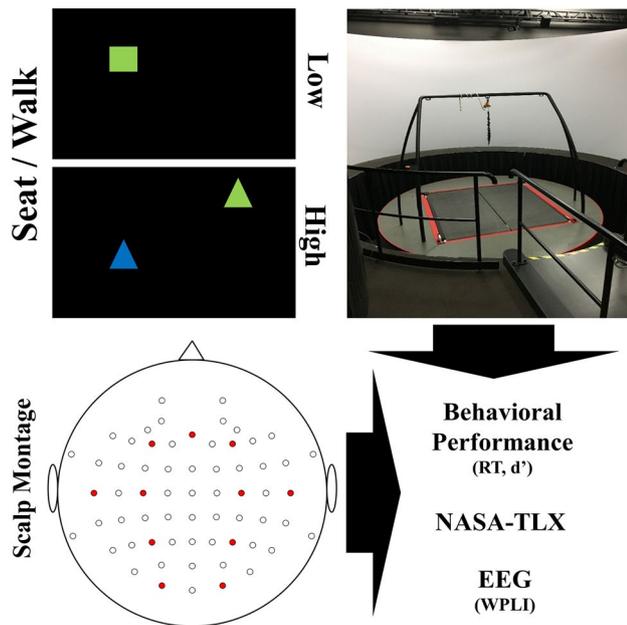


Fig. 1 Experimental platform where individuals performed a cognitive task under two levels of demand (low and high) while being seated or walking on a treadmill within the CAREN system. While participants completed each experimental condition, behavioral performance along with EEG were recorded. The scalp montage reflects the approximate locations of each sensor where EEG data were recorded from (sensors in red reflect the traditional montage whereas the comprehensive montage included all the sensors). *RT* response time, *WPLI* weight phase lag index

while seated and while walking at a self-selected speed on a dual-belt treadmill within a Computer Assisted Rehabilitation Environment (CAREN; Motekforce Link, Amsterdam, The Netherlands; Fig. 1). Completion of the four 8 min experimental conditions (i.e., seated while performing the low cognitive-demand task, seated while performing the high cognitive-demand task, walking while performing the low cognitive-demand task and walking while performing the high cognitive-demand task) was counterbalanced across participants. Prior to beginning testing, participants engaged in a 4 min acclimation period walking at a comfortable self-selected speed on the treadmill. For each participant, the mean self-selected speed during the final 30 s of this acclimation period determined the treadmill speed for the walking conditions (mean \pm standard deviation treadmill speed: 1.22 ± 0.15 m/s). Additionally, one treadmill belt was set to move at the participant's self-selected speed during the seated conditions to standardize acoustical noise generated by the treadmill across seated and walking conditions. At the end of each experimental condition, the NASA-TLX was administered to obtain a self-report assessment of overall perceived workload via six dimensions (i.e., mental demand, physical demand, temporal demand, perception of performance, effort and frustration). The score for each of the six

dimensions was computed, separately (Hart 2006; Hart and Staveland 1988). Once the NASA-TLX was completed, participants were allowed a 2 min break to reduce the effect of fatigue.

Cognitive task

The cognitive task was composed of various shapes (squares, circles, and triangles) and colors (blue, green, and red) displayed for 500 ms, with a random inter-stimulus interval of 100–1000 ms on a large 180° projection screen immediately in front of the treadmill (approximately 3 m away). All stimuli were centrally presented to minimize head and eye movement. Difficulty of the cognitive task was determined by the combination in which the shapes and colors appeared on the screen. Specifically, one shape was displayed at a time for the low cognitive-demand task while two shapes were displayed at a time for the high cognitive-demand task. For the low level of challenge, participants were instructed to respond every time a square of any color appeared on the screen by pressing a button on a handheld wireless game controller, as quickly and accurately as possible. For the high level of challenge, participants were instructed to respond, as quickly and accurately as possible, every time the two stimuli were of the same shape or of the same color (e.g., a red square and a red circle, or a green triangle and a red triangle) using the same game controller. Performance on the cognitive task was indexed by response time (i.e., time elapsed between the appearance of the target stimuli on the screen and the response of the individual) for correct responses only and d' (i.e., accounts for correct hits and false alarms while indicating the capacity to detect information).

Electrophysiological data collection and signal processing

Throughout each experimental condition, EEG was recorded from sixty-four scalp sites (extended 10–20 system) at a sampling frequency of 1000 Hz transmitted wirelessly.³ The EEG data were online referenced to the left earlobe and a common ground was employed at the FPz site on the scalp. All electrode impedances were maintained below 10 k Ω and band pass filters were set at 0.01–100 Hz throughout the study. The EEG signal was amplified, digitized and linked to recording software.⁴

³ EEG data were acquired using an actiCAP EEG system and wirelessly transmitted through the MOVE system (Brain Products GmbH, Munich, Germany).

⁴ The EEG signal was amplified and digitized using a BrainAmp DC Amplifier linked to Brain Vision Recorder software version 2.1 (Brain Products GmbH, Munich, Germany).

Signal processing of the EEG data was conducted using analyzing software.⁵ Continuous data recorded during each condition was re-referenced to an averaged ears montage offline before further processing. To minimize any transient effects at the beginning or end of the task (e.g., task adjustment, fatigue), data recorded between 3 and 6 min during each experimental condition were extracted for analysis. Data extracted from this 3 min time window were low-pass filtered at 50 Hz with a 48-dB roll off and notch filtered at 60 Hz using a zero phase shift Butterworth filter offline. Subsequently, a technique referred to as pruning (Onton et al. 2006) was performed to visually inspect the data and remove all non-stereotyped artifacts (e.g., motion) from further analysis. Following the removal of non-stereotyped artifacts, eye movement artifact was reduced using an ICA-based artifact rejection function embedded within the analyzer software (BrainProducts 2013). The VEOG and HEOG algorithms identified ICA-derived components that accounted for 70% and 30% of the amount of variance in the entire signal from the FP2 (served as the VEOG channel) and AF7/AF8 channels (served as the bipolar HEOG channel), respectively. These components were removed from the raw EEG signal, which was then reconstructed for further processing. Although this ICA approach was employed to mainly focus on eye artifact, artifact due to body motion or other perturbations were removed whenever identified. After ICA-based artifact rejection, the 3 min block of data was epoched into 1 s sweeps and baseline corrected using the mean potential (0–1000 ms). Epochs were visually inspected to remove any remaining artifact.

Connectivity analyses were conducted by computing the Weighted Phase Lag Index (WPLI), which measures the distribution of phase angle differences between two sensors along the complex plane across various frequency bandwidths (Cohen 2014; Vinck et al. 2011; Wang et al. 2017). The phase angle differences are weighted based on their distance from the real axis, such that phase angle differences closest to the real axis will have less influence on the final estimate of cortical connectivity, thus limiting the risk of artificial noise (e.g., volume conduction) argued to bias EEG coherence analyses (Nunez et al. 1997).

Thus, cortico-cortical communication was evaluated by employing the Weighted Phase Lag Index (WPLI) defined as:

$$WPLI = \frac{|E\{|\Im\{X\}|\text{sgn}(\Im\{X\})\}|}{E\{|\Im\{X\}|\}},$$

where $\Im\{X\}$ represents the imaginary component of the cross-spectrum between two electrodes, sgn represents the

sign function, and $E\{.\}$ represents the expected value operator. For a more detailed definition, please refer to Vinck et al. (2011). In the current study, WPLI was calculated across 1-Hz bins and averaged across the frequency bandwidths theta (4–7 Hz), low-alpha (8–10 Hz) and high-alpha (11–13 Hz) for all possible electrode pairs (2016 total pairs). WPLI values were then subjected to a Fisher z transformation prior to statistical analysis to approximate a normal distribution.

Cerebral cortical connectivity analysis

In this study, two montages were employed to examine cerebral cortical networking (see Fig. 1). First, the WPLI was assessed using a traditional scalp montage centered over the motor planning region (electrode Fz) due to its common use in cognitive–motor studies (Deeny et al. 2003; Gentili et al. 2015; Rietschel et al. 2012). In particular, WPLI values between the premotor region (Fz) and the frontal (F3 and F4), central (C3 and C4), temporal (T7 and T8), parietal (P3 and P4) and occipital regions (O1 and O2) for both the left and right hemispheres were evaluated.

In addition, a secondary analysis was conducted which employed statistical graph methods applied to the whole scalp. Such an analysis allowed for the identification of network topologies for which changes in connectivity under various cognitive–motor demands can inform any changes in cortico-cortical communication underlying variations in mental workload in a more detailed manner. This analysis is based on a recently developed graph approach that can detect networks with well-organized topology and a high proportion of differentially (increased/decreased connectivity) expressed edges (Chen et al. 2015, 2016, 2017). In essence, this graph connectivity analysis was employed to identify: (1) which connections are associated with changes in cortical dynamics of mental workload in response to varying cognitive–motor demands as well as (2) whether these connections encompass organized latent network topological structures. The statistical tests were conducted at the network level instead of individual edges which integrated effect sizes of connections. In addition, the graph combinatorics for edges detecting changes in cortical communication due to varying cognitive–motor demands were distributed in an organized topological structure. As with the analysis which employs the traditional montage previously presented, this graph theory model considered undirected connectivity (i.e., undirected edges). Thus, by integrating topological, differentially expressed, and localized edge features, this method can detect modification in cortical networking, thus providing insight into systematic changes of cortical connectivity modulation to index changes in mental workload under various levels of challenge. In such an approach, the 64 sensors covering the whole scalp were modeled as a graph, $G=(S,$

⁵ BrainVision Analyzer software version 2.0 (Brain Products GmbH, Munich, Germany) was used for EEG signal processing.

E), where the node set S represents EEG sensor locations, and an edge $e_{ij} \in E$ which connects the sensors i and j (e.g., F3–P4) (Chen et al. 2015, 2016, 2017). This approach allows for the fusion of graph topological properties and localized effect size on specific connections/edges. The results not only reveal which specific networks respond to the change of a particular cognitive–motor demand, but also provide for inferences of specific connections within the networks. The technical details of the approach can be found in Chen et al. (2015, 2016, 2017). To further characterize the functional connectivity features of any identified with this approach, both the global and local efficiencies were computed on the WPLI values by employing the Brain Connectivity Toolbox (Rubinov and Sporns 2010). These measures of efficiency can serve as an index of the level of functional integration representing how efficiently the information between nodes of a given network is exchanged at the global (all nodes of the network) and local (neighborhood of each node) level (Bullmore and Sporns 2009).

Statistical analysis

Response time, d' and NASA-TLX scores were subjected to a 2×2 (Difficulty [Low vs High] \times Condition [Seated vs Walking]) repeated-measures ANOVA. Post hoc analyses were computed using the Tukey's HSD test, when necessary. The Greenhouse–Geisser correction was employed when the sphericity assumption was violated and the p values reported are based on the corrected degrees of freedom. Partial eta squared (η_p^2) and Cohen's d effect sizes are also provided when appropriate. All criterion alpha levels were set to $p < 0.05$. Additionally, specific p values are reported unless significance was below the 0.001 threshold, in which case $p < 0.001$ was reported for conciseness.

Using the traditional scalp montage, centered over the motor planning region, WPLI values for each of the frequency bandwidths were subjected to separate $2 \times 2 \times 2 \times 5$ (Difficulty [Low vs High] \times Condition [Seated vs Walking] \times Hemisphere [Left vs Right] \times Region [Frontal, Central, Temporal, Parietal, and Occipital]) repeated-measures ANOVAs. When needed, post hoc analyses for all frequency bandwidths were computed using the Tukey's HSD test. Depending on the epsilon value, the Greenhouse–Geisser or Hyndt–Feldt correction was applied when the sphericity assumption was not met. All p values reported are based on the corrected degrees of freedom. Partial eta squared (η_p^2) and Cohen's d effect sizes were also provided, when appropriate. All criterion alpha levels were set to $p < 0.05$. Specific p values were reported unless significance was below the 0.001 threshold, in which case $p < 0.001$ was reported for conciseness.

For the graph connectivity approach, first a series of linear mixed effect models were run on each edge for assessing

any main (Difficulty [Low vs High] or Condition [Seated vs Walking]) or interaction (Difficulty \times Condition) effects giving p_{ij} values for each edge e_{ij} between the nodes i and j (i.e., each pair of EEG sensors). Then, for each edge e_{ij} a weight $W_{ij} = -\log(p_{ij})$ was computed which, when elevated, reflected an effect size on this edge between the contrasts of interest. As such, the weighted matrix W was employed for identifying network alterations depending on the contrasts of interest. Then, the use of a combination of parsimonious differential brain connectivity network identification, k -partite algorithms and permutation test allowed for identifying statistically significant (network level p value) network alterations (for further details about this approach, see Chen et al. (2015, 2016, 2017)). In addition, the mean weighted degree,⁶ global and local efficiency for each network and contrast of interest were compared by employing paired samples t tests or Wilcoxon signed-rank tests depending on whether the assumption of normality (assessed by a Kolmogoroff–Smirnov test) was met or not. The false discovery rate was employed to account for the multiple comparisons conducted to compare the weighted degree, global and local efficiency measures for the different relevant networks and contrast.

Results

Behavioral performance

Performance on the secondary cognitive task was comparable across all conditions as no significant main effect or interaction was detected for d' ($p > 0.05$). However, statistical analysis conducted for response time revealed a main effect of Difficulty ($F(1, 12) = 96.24, p < 0.001, \eta_p^2 = 0.89$), which was superseded by a significant Difficulty \times Condition interaction ($F(1, 12) = 7.46, p = 0.018, \eta_p^2 = 0.38$). Post hoc analyses revealed that response times were greater during the walking compared to the seated conditions while performing the secondary concurrent task under high demand ($p = 0.027, d = 2.51$), whereas no difference was observed for the low task demand ($p > 0.05$); see Fig. 2.

NASA-TLX

The statistical analysis of the NASA-TLX scores revealed a main effect of Difficulty as participants reported increased levels of mental demand ($F(1, 13) = 24.39, p < 0.001$,

⁶ The weighted degree was computed for the frontal, central, temporal, parietal and occipital regions whenever identified as involved in the changes in connectivity for each network for the relevant contrast of interest.

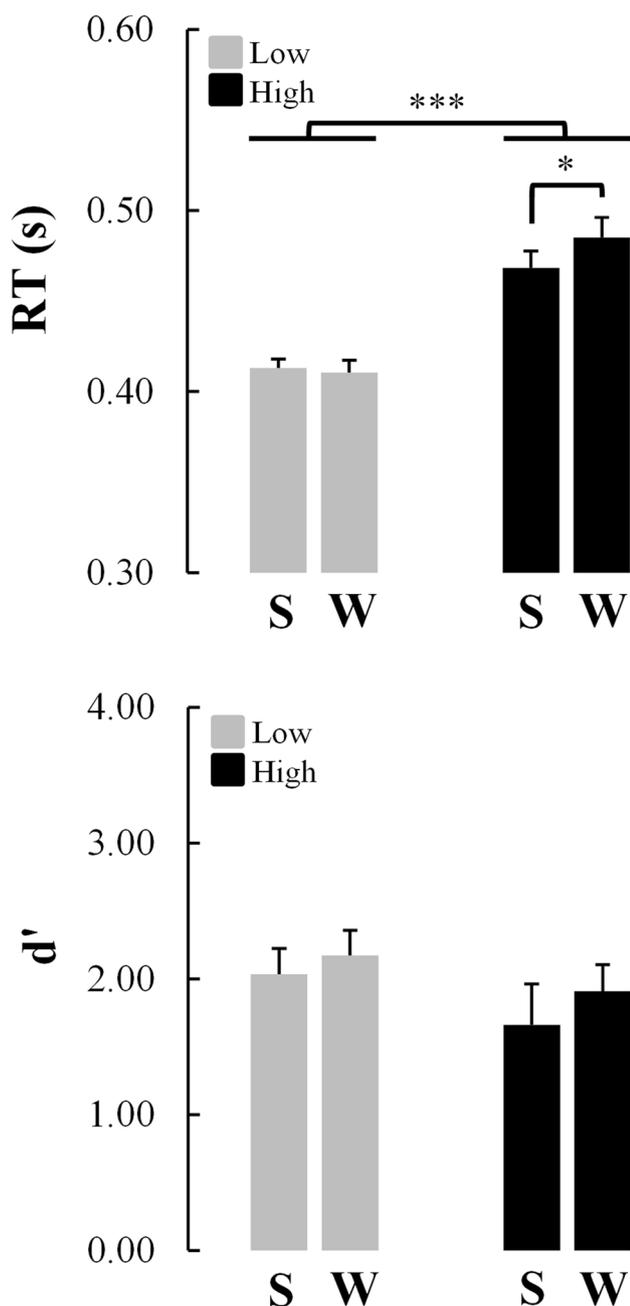


Fig. 2 Behavioral performance on the cognitive task under a low (gray bars) and high (black bars) demand during the seated and the walking conditions for RT (top panel) and d' (bottom panel). RT response time. S seat, W walk. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

$\eta_p^2 = 0.65$), temporal demand ($F(1, 13) = 11.59, p = 0.005, \eta_p^2 = 0.47$), performance ($F(1, 13) = 21.21, p < 0.001, \eta_p^2 = 0.62$), effort ($F(1, 13) = 54.46, p < 0.001, \eta_p^2 = 0.81$) and frustration ($F(1, 13) = 11.24, p = 0.005, \eta_p^2 = 0.46$) for the high level of challenge compared to the low level of challenge. Furthermore, a main effect of Condition was revealed as participants reported increased levels of physical demand ($F(1, 13) = 24.26, p < 0.001, \eta_p^2 = 0.65$) and effort ($F(1,$

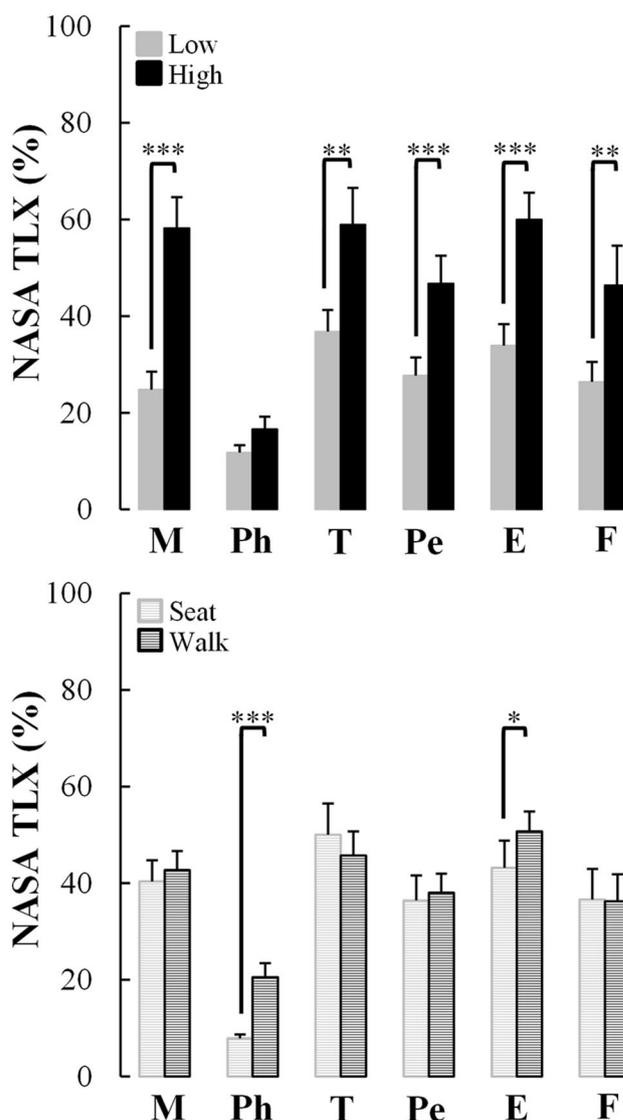


Fig. 3 Mean and standard error for the scores of each NASA-TLX dimension for the cognitive task under low (gray bars) and high (black bars) demand (top panel) as well as for the seated (gray striped bars) and walking (black striped bars) conditions (bottom panel). M mental demand, P physical demand, T temporal demand, Pe performance, E effort, F frustration (see Hart and Staveland 1988 for the description of each question). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

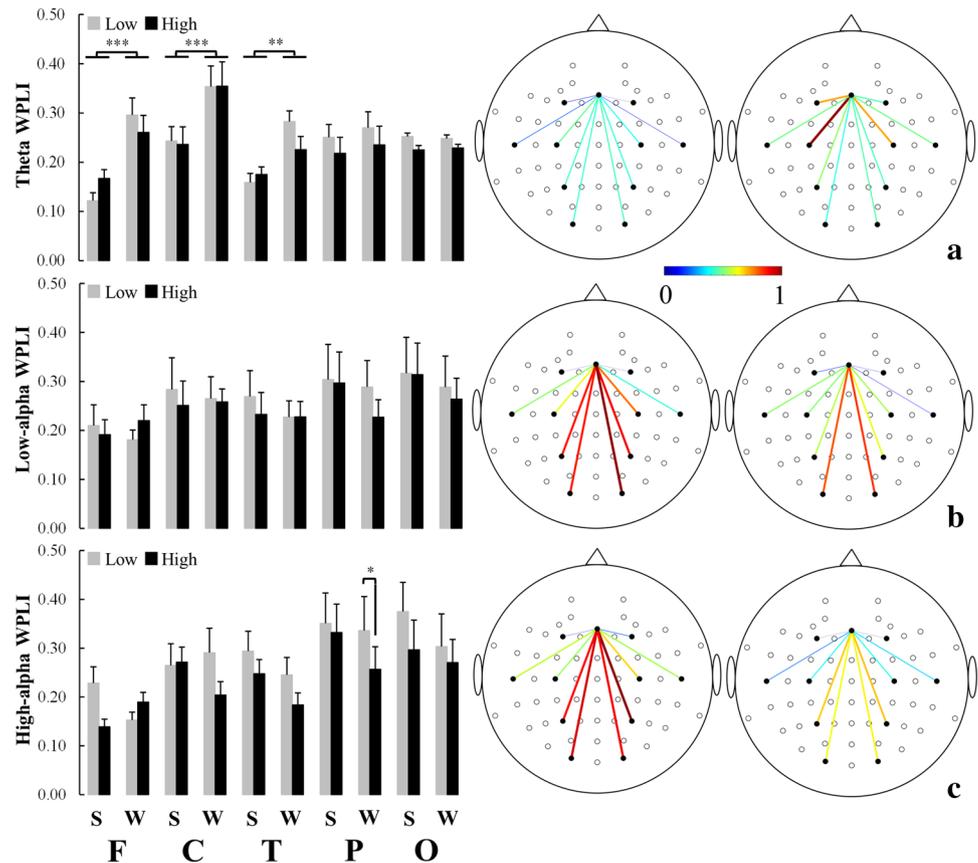
13) = 6.30, $p = 0.026, \eta_p^2 = 0.33$) for the walking compared to the seated conditions (Fig. 3).

Traditional montage centered over premotor cortical region

Theta

Statistical analysis of the theta band revealed a main effect of Condition ($F(1, 13) = 7.92, p = 0.015, \eta_p^2 = 0.38$). However,

Fig. 4 Changes in the magnitude of cerebral cortico-cortical communication (left column) and the respective scalp topographies (right two columns) using the traditional montage for the theta (top row), low-alpha (middle row) and high-alpha (bottom row) frequency bandwidths computed between the frontal (planning region; Fz) and the central, temporal, parietal, occipital regions as participants performed the low (gray bars) or high (black bars) cognitive task demand while being seated and walking. Enhanced connectivity between electrodes is illustrated by thicker lines with warmer colors whereas weaker connectivity is depicted by thinner lines with colder colors. *S* seat, *W* walk, *F* frontal, *C* central, *T* temporal, *P* parietal, *O* occipital. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$



this main effect was superseded by a significant Condition \times Region interaction ($F(2.16, 28.04) = 7.43, p = 0.002, \eta_p^2 = 0.36$). Post hoc analyses revealed connectivity between Fz and the frontal ($p < 0.001, d = 1.49$), central ($p < 0.001, d = 0.89$), as well as the temporal ($p = 0.006, d = 1.21$) cortical regions increased significantly during the walking compared to the seated conditions, regardless of the demands of the secondary cognitive task (Fig. 4a).

Low-alpha

No significant results of interest were observed for the low-alpha band (Fig. 4b).

High-alpha

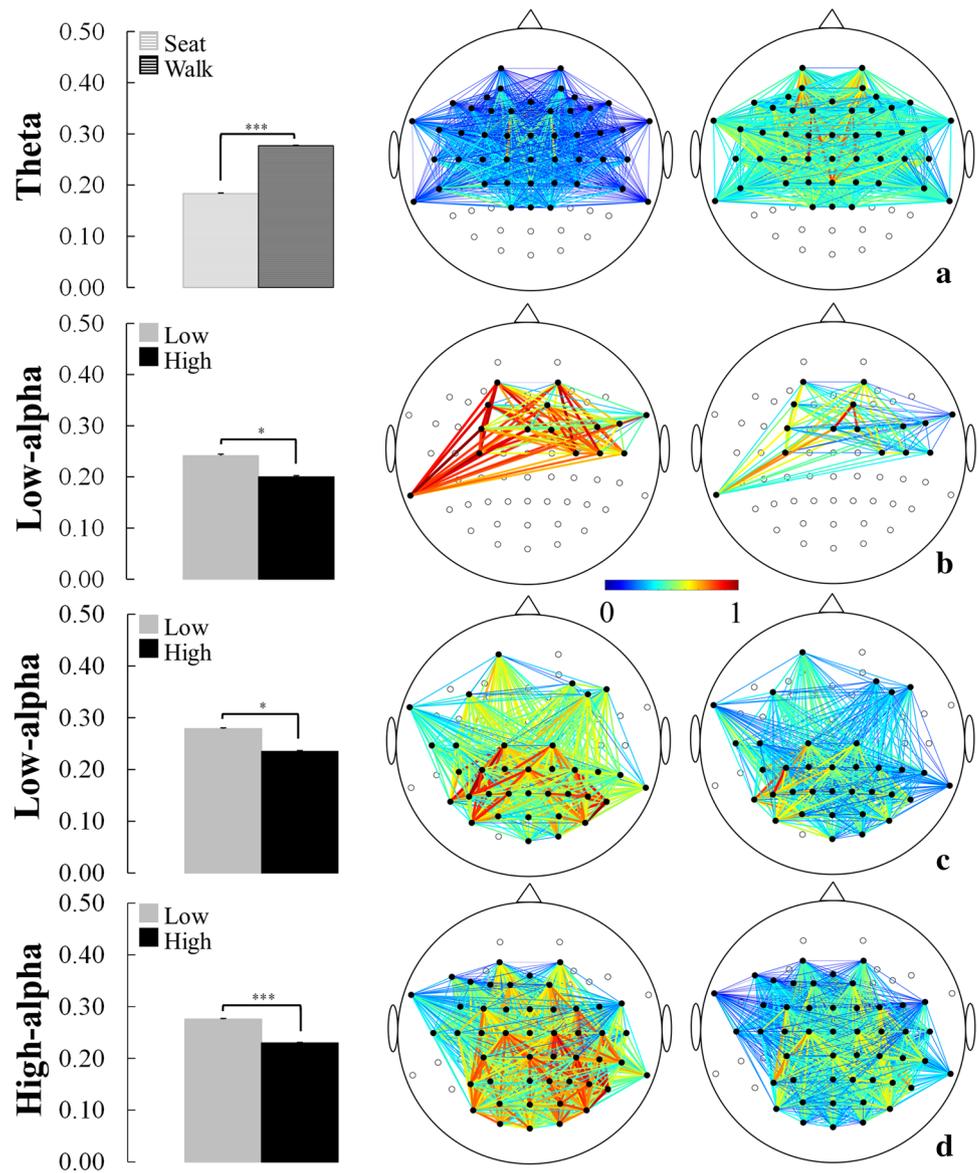
For the high-alpha band, statistical analysis revealed a significant Difficulty \times Condition \times Region interaction ($F(1.77, 23.02) = 4.37, p = 0.028, \eta_p^2 = 0.25$). Post hoc analyses revealed greater connectivity between Fz and the parietal ($p = 0.05, d = 0.36$) cortical region for the low compared to the high level of difficulty during the walking conditions (Fig. 4c).

Comprehensive montage based on graph connectivity analysis

Theta

For the theta band, there was a main effect of Condition with one network composed of 47 nodes detected ($p < 0.001$). Within this identified network, the magnitude of cortical networking increased during the walking compared to the seated conditions. The differentially expressed edges within the detected network along with the mean change in magnitude of those edges between seated and walking conditions are displayed in Fig. 5a. In addition, the findings revealed that the mean weighted degree for the frontal ($t(13) = -4.71, p = 0.003, d = 1.26$), central ($t(13) = -4.14, p = 0.005, d = 1.08$), temporal ($t(13) = -5.30, p = 0.002, d = 1.42$) and parietal ($t(13) = -4.16, p = 0.005, d = 1.12$) regions was elevated during the walking compared to the seated conditions. Also, the results revealed that both mean global ($t(13) = -4.65, p = 0.002, d = 1.24$) and local ($t(13) = -4.82, p = 0.002, d = 1.29$) efficiency within this network increased during the walking relative to the seated conditions (see Fig. 6a).

Fig. 5 Changes in the magnitude of cerebral cortico-cortical communication (left column) and the respective scalp topographies (right two columns) using the comprehensive montage for the theta (top row), low-alpha (middle two rows) and high-alpha (bottom row) frequency bandwidths as participants performed the low (gray bars) or high (black bars) cognitive task demand while being seated (stripped gray bars) and walking (stripped black bars). Enhanced connectivity between electrodes is illustrated by thicker lines with warmer colors whereas weaker connectivity is depicted by thinner lines with colder colors. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$



Low-alpha

A main effect of Difficulty in the low-alpha band was observed, revealing two networks. The first network was composed of 15 nodes ($p = 0.03$) and the second network was composed of 35 nodes ($p = 0.04$). For both networks, the magnitude of cortico-cortical communication decreased as individuals completed the high compared to the low demand on the secondary cognitive task. Figure 5b, c shows the differentially expressed edges within the two detected networks as well as the mean change in magnitude of those edges between the low and high levels of challenge on the secondary cognitive task. Also, as the task demand increased, a reduction of the mean weighted degree in the frontal ($z = 2.17, p = 0.050, d = 0.55$), central ($z = 2.35, p = 0.040, d = 0.67$) and temporal ($t(13) = 2.86, p = 0.038, d = 1.24$)

regions was observed for the first network. No significant decrease of the mean weighted degree was observed for the second network ($p > 0.12$ for all comparisons). Furthermore, the findings revealed a reduction of both mean global (first network: $z = 2.35, p = 0.025, d = 0.70$; second network: $t(13) = 1.73, p = 0.11, d = 0.46$) and local (first network: $z = 2.61, p = 0.018, d = 0.74$; second network: $t(13) = 3.20, p = 0.007, d = 0.86$) efficiency within both networks during the high relative to the low task demand (see Fig. 6b, c).

High-alpha

The high-alpha band revealed a main effect of Difficulty with one network composed of 48 nodes detected ($p < 0.001$). Similar to the findings for the low-alpha band, the magnitude of cortico-cortical communication within the detected

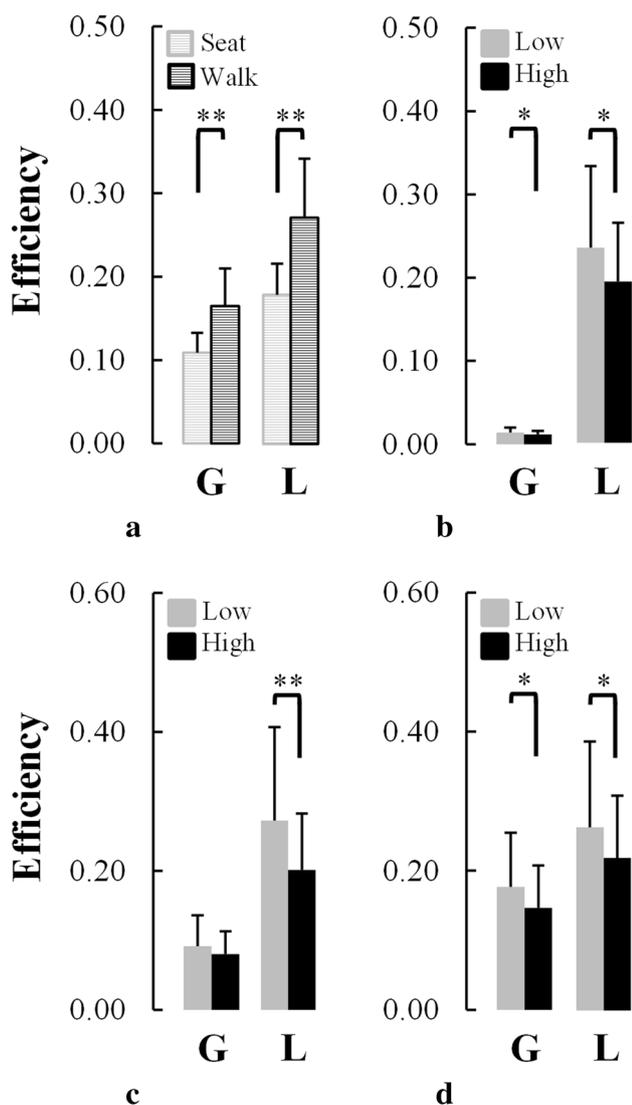


Fig. 6 Mean global and local efficiency of the functional connectivity in the four networks identified with the comprehensive montage in the theta (a), low-alpha (b, c) and high-alpha (d) bandwidths as individuals performed the low (gray bars) or high (black bars) cognitive task demand while being seated (stripped gray bars) and walking (stripped black bars). *G* global, *L* local. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

network for the high-alpha band decreased during the high compared to low demand on the secondary concurrent cognitive task. The differentially expressed edges within the detected network and the mean change in magnitude of those edges between the low and high level of difficulty are displayed in Fig. 5d. Moreover, as the task demands increased, the mean weighted degree was significantly attenuated for the central ($z = 2.17$, $p = 0.050$, $d = 0.57$), temporal ($t(13) = 2.96$, $p = 0.038$, $d = 0.80$), occipital ($z = 2.23$, $p = 0.050$, $d = 0.69$) along with a tendency for the parietal ($z = 2.10$, $p = 0.052$, $d = 0.60$) regions. Finally, the

findings revealed that within this network both mean global ($t(13) = 2.69$, $p = 0.025$, $d = 0.72$) and local ($t(13) = 2.37$, $p = 0.038$, $d = 0.64$) efficiency decreased during the high compared to the low task demand (see Fig. 6d).

Discussion

Overall the findings revealed that as the cognitive–motor demands increased, performance on the concurrent secondary task decreased while the perceived mental workload and task difficulty increased. These changes corresponded with an elevation and reduction of theta and low-/high-alpha functional connectivity, respectively. Specifically, an elevation of the cognitive–motor demands due to the task condition (seated vs. walking) resulted in an elevation of theta connectivity for both the traditional and comprehensive montages. The former revealed that elevated cognitive–motor demands led to enhanced theta functional connectivity between the planning (Fz) and the frontal, central and temporal regions. The latter confirmed these results, such that an elevation of cognitive–motor demands resulted in increased theta connectivity in a large fronto-centro-temporo-parietal network without including the parieto-occipital and occipital regions. Furthermore, as the demands on the secondary concurrent cognitive task (low vs. high) increased, a reduction of low-/high-alpha connectivity was observed. Specifically, the traditional montage revealed a reduction of high-alpha connectivity between the planning and parietal regions as cognitive–motor demands increased during walking. The comprehensive montage extended these findings by revealing a reduced low-alpha connectivity in a focused fronto-centro-temporal network as well as in a distinct denser more posterior fronto-temporo-parieto-occipital network. Finally, an elevation of cognitive–motor task demands led to attenuated high-alpha connectivity of a widespread network covering almost the entire scalp.

Changes in theta functional connectivity

The enhanced theta connectivity observed under increased cognitive–motor demands is generally in agreement with the notion that cortico-cortical communication increases under high levels of challenge (Deeny et al. 2003, 2009; Gentili et al. 2015; Rietschel et al. 2012). Specifically, the enhanced fronto-centro-temporo-parietal theta functional connectivity observed in both montages suggests that there was greater cortical communication, mean weighted degree, and (local, global) efficiency between executive/planning, motor, sensory and cognitive processes when participants were faced with increased cognitive–motor demands. The comprehensive approach, in particular, revealed that this large-scale network involved a dense

pairing between the prefrontal/frontal and the temporo-parietal, centro-parietal and parietal regions (representing 81% of all network pairs). The prominence of the anterior frontal regions being coupled to temporal, central and parietal regions is consistent with the notion that the frontal regions play a pivotal role for long-range communication which modulates in a top-down manner the engagement of sensory and cognitive resources of other cortical areas (Cavanagh and Frank 2014; Clayton et al. 2015; Cohen 2011; Miller and Cohen 2001). More precisely, enhanced fronto-parietal theta connectivity further integrates sensorimotor information, while both regions are known to be essential in attentional control. This latter point is supported by prior efforts, which have suggested that fronto-parietal theta connectivity is critical to increase attentional vigilance/orienting and enhanced sensory processing to resolve action/response situations. More generally, it was proposed that the fronto-parietal network may subserve attentional control, which is potentially mediated by the central executive system managing working memory to modulate the initiation and regulation of the relevant control processes (Cavanagh and Frank 2014; Cohen 2011; Corbetta and Shulman 2002; Doesburg et al. 2009, 2016; Harper et al. 2017; Kitaura et al. 2017; Sauseng et al. 2005, 2007). This perspective is also supported by recent efforts, which have proposed that working memory (and possibly the central executive) can influence the degree to which attention is allocated (Gentili et al. 2018; Ishii et al. 2014; San Miguel et al. 2008; Scheer et al. 2016; Shaw et al. 2018; Simon et al. 2016).

Therefore, in the present study, an elevation in challenge due to a change in the condition performed (dual-task walking relative to being seated while performing a concurrent task) resulted in greater cognitive–motor demands and, in particular, a greater need for integration of sensorimotor and attentional resources. In turn, these increased cognitive–motor demands may lead to further recruitment of processing resources devoted to the integration of sensorimotor information sent to working memory. This elevation would expand the overall quantity of information to be held in this memory system, thereby engaging the central executive to augment attentional allocation to the primary task (here walking) as reflected by an enhanced theta fronto-parietal connectivity (Gentili et al. 2018; San Miguel et al. 2008; Scheer et al. 2016; Shaw et al. 2018; Simon et al. 2016). When considering the multiple resources model of mental workload proposed by Wickens et al., the augmentation of the challenge (seated vs. walking) would result in increased attentional, sensorimotor integration and working memory demands leading to an elevated recruitment of the corresponding resources which would in turn collectively contribute to an elevation of mental workload (Hancock and Warm, 1989; Wickens 2002, 2005, 2008; Young et al. 2015).

Beyond the fronto-parietal dynamics, changes in fronto-temporal and fronto-central connectivity were observed. It has been suggested that the fronto-temporal theta connectivity is engaged during target detection, which potentially reflects context updating or stimulus–response activation. This network may be involved in conflict processing during stimulus classification of events and retrieval/activation of previously encoded stimulus–response relationships during task performance (Bledowski et al. 2004; Cavanagh and Frank 2014; Harper et al. 2017; Verleger et al. 2014, 2016). Thus, the enhanced fronto-temporal theta connectivity observed here may reflect an increased engagement of the resources for detection and processing of the visual stimuli presented during the concurrent cognitive task in an effort to maintain performance while walking. It must be noted that although an enhanced recruitment of cognitive–motor processes may represent an effort to maintain performance, such an adaptive response is not necessarily enough to fully compensate for the elevation in challenge. For instance, under low cognitive demand, performance was maintained during seated and walking conditions (similar RT and d'). However, when the cognitive demand increased, information processing and response generation velocity were degraded (i.e., increased RT). Nevertheless, only this performance component was deteriorated since the accuracy of the response (i.e., similar d') and also walking patterns (e.g., stride length mean and variability; see Pruziner et al. 2019 for details) remained unchanged as cognitive–motor demands increased. In addition, the enhanced fronto-central theta connectivity when participants were engaged in dual-task walking (relative to the seated condition) may represent increased cortico-cortical communication between executive/planning regions and the central (premotor/motor) regions. This recruitment of motor resources is likely needed to regulate locomotion patterns under task and/or environmental constraints, such as dual-task walking (Artoni et al. 2017; Beurskens et al. 2016; Holtzer et al. 2011; Mirelman et al. 2014).

Another specific topological feature of this theta network was that changes in connectivity did not involve the parieto-occipital and occipital regions when the task was performed in the seated relative to the walking condition. This may seem contradictory since cognitive task performance while being seated has only one source of visual information (object shape and color to be detected on the screen), whereas cognitive task performance while walking has two different sources of visual information (one related to the cognitive task and one to locomotion regulation) that needs to be coordinated. The theta network in the current study revealed no modulation of the parieto-occipital and occipital regions, which are involved in visual processing (Beurskens et al. 2016; Chien et al. 2014; Nomura et al. 2005). However, part of the network connectivity modulated in response to changes in cognitive–motor task demands included the

temporo-parietal region. This region is well known for integrating both visual and somatosensory information while also being a part of the attentional network and involved in controlling attentional shifting (here between the primary and secondary task) (Bzdok et al. 2013; Krall et al. 2015; Mars et al. 2012). Also, with this particular data set it was previously observed that parietal and occipital theta power increased during the walking relative to the seated conditions, suggesting that these regions are somewhat modulated in this bandwidth due to enhanced sensory processing (Shaw et al. 2018). Thus, theta parieto-occipital and occipital connectivity, at least in this specific task, may not have been essential to respond to the increased cognitive–motor demands due to a change in task conditions.

As a whole, the elevation of the fronto-centro-temporo-parietal theta connectivity observed in the current study may reflect the need to further recruit sensory/sensorimotor integration, attentional and working memory resources in an effort to maintain stimulus–response processing performance as well as locomotion pattern regulation in response to an elevation of the corresponding cognitive–motor demands during dual-task walking. Such an enhanced engagement of cognitive–motor resources would be the main contributor underlying an elevation of the mental workload (Hancock and Warm 1989; Wickens 2002, 2005, 2008; Young et al. 2015).

Changes in alpha functional connectivity

Both montages revealed that enhanced demands (high vs. low) on the secondary cognitive task during both seated and walking conditions resulted in deteriorated performance, increased perceived mental workload and task difficulty, attenuated low-/high-alpha connectivity, as well as a reduced mean weighted degree, and (local, global) efficiency. Namely, the traditional montage revealed that increased demands on the secondary cognitive task led to reduced fronto-parietal high-alpha connectivity. Moreover, the more comprehensive network analysis revealed that enhanced task demands resulted in a decreased low-alpha connectivity within: (1) a focused fronto-central network with a specific connection to the left temporo-parietal region and (2) a distinct much larger and denser centro-parieto-occipital network with connections to the left prefrontal, frontal, left temporal as well as right frontal and temporo-parietal regions. Also, increased demands on the secondary cognitive task led to reduced high-alpha connectivity in a dense fronto-centro-temporo-parieto-occipital network encompassing almost the entire scalp.

Various interpretations of these network dynamics could be considered here. Although changes in alpha functional connectivity may reflect modulation of cortico-cortical communication in attempt to maintain performance when

faced with elevated task demands, the exact nature of this communication remains unknown (Doesburg et al. 2009). In particular, it was previously proposed that the relationship between long-range synchronization/desynchronization and more focal activations/deactivations during cognitive processing is complex since it involves both inhibition and activation of specific cortical regions. This is supported by the observation that an increase in functional connectivity between regions revealed both negative and positive fMRI-bold biomarkers during cognitive processing (Mizuhara et al. 2005). As such, changes in alpha functional connectivity between cortical regions could either represent a modulation in the transmission of the amount and degree of detail of task relevant information or alternatively reflect the recruitment of inhibitory or excitatory processes in the targeted regions depending on the processing needs (Doesburg et al. 2009; Wang et al. 2016).

Therefore, in the context of this work the observed reduction of low-/high-alpha connectivity could be interpreted either as a reduced transmission of task relevant information or as a top-down frontally mediated attenuation of inhibition of targeted regions to recruit additional cognitive–motor resources when encountering elevated task demands (Buzsaki and Draguhn 2004; Doesburg et al. 2009; Fries 2005). The first interpretation is in line with numerous previous cognitive–motor studies, which suggest that an increase in the recruitment of cognitive–motor resources to meet the corresponding task demands would result in elevated mental workload as indicated by enhanced alpha connectivity. The enhanced alpha connectivity is reflective of increased cortico-cortical communication to enhance intercortical information transmission to maintain or even enhance performance (e.g., Corbetta et al. 2014; Deeny et al. 2003, 2009; Gentili et al. 2015; Ghasemian et al. 2017; Rietschel et al. 2012; Teel et al. 2014). Thus, in the context of this work, if alpha cortico-cortical communication reflects the quantity of information transmitted between cortical regions as the secondary cognitive task demand increases, an elevation (not a reduction) of alpha connectivity should have been observed. It could still be argued that reduced alpha connectivity suggests that participants disengaged from the task due to an overwhelming elevation of cognitive–motor demands. However, this is not supported by a prior analysis of the same data set, which revealed a reduction of an event-related potential marker of attentional reserve (novelty-P3 amplitude to task-irrelevant auditory stimuli) and low/high-alpha power over the entire scalp. These findings indicate an increased recruitment of attentional resources to negotiate an augmentation of task demands, which ultimately contributed to an elevation of mental workload (Shaw et al. 2018; Wickens 2002, 2008; Young et al. 2015). A task disengagement due to an elevation of cognitive–motor demands would have been accompanied with no additional recruitment of

attentional resources, reduced theta connectivity and also a decrement of the d' index; however, none of these were observed. The findings suggest that a different mechanism underlying alpha connectivity may have been engaged to successfully dual-task walk in this study.

Conversely, the second interpretation, based on the modulation of inhibition (e.g., reduction of its efficiency), provides a plausible mechanism to interpret the low-/high-alpha connectivity patterns observed here. A possible mechanism would be that as the cognitive–motor task demand increases, the frontal region (in particular its anterior portions) disinhibits the targeted cortical regions, thus increasing their engagement to further recruit attentional, working memory and sensorimotor integration resources contributing to elevate the mental workload in an effort to maintain performance (Buzsaki and Draguhn 2004; Cavanagh and Frank 2014; Cohen 2011; Corbetta and Shulman 2002; Doesburg et al. 2009, 2016; Fries 2005; Harper et al. 2017; Kitaura et al. 2017; Sauseng et al. 2005, 2007; Wang et al. 2016). This interpretation is consistent with the notion that: 1) the connectivity involving frontal regions is largely represented in the three alpha networks identified here (about 90% and 30% for the first and second low-alpha network and 60% for the high-alpha network) and 2) the reduction of alpha power previously observed with this data set (Shaw et al. 2018). In addition, a reduction of alpha functional connectivity due to enhanced task demands is consistent with prior work, which revealed similar reductions in cortical networking (also accompanied by decreased alpha power) when elevated demands lead to further engagement of attentional, working memory and visuomotor coordination resources (Dai et al. 2017; Nikolov 2013; Sauseng et al. 2005; Siegel et al. 2008).

Considering this inhibition-based mechanism, the reduced low-alpha connectivity in the first focused fronto-central network with a connection to the left temporo-parietal region may reflect an attenuated cortical inhibition to enhance general attention processes, such as basic alertness, vigilance or arousal in response to increased task demands (Babiloni et al. 2011; Del Percio et al. 2011). Possibly, the frontal region may disinhibit the central regions to increase resources related to general attention to monitor hand motor pattern for response selection to the visual stimuli as well as locomotion regulation while performing the dual-task. Simultaneously, the left temporo-parietal region would be further engaged to subserve attentional mechanisms, such as attention re-orienting and processing resources to deal with infrequent nonstandard stimuli (DiQuattro and Geng 2011; Geng and Mangun 2011; Kucyi et al. 2012; Serences et al. 2005; Vossel et al. 2008, 2014; Weidner et al. 2009). Similarly, the attenuated low-alpha connectivity in the second distinct and denser prefrontal/frontal-centro-temporo-parieto-occipital networks may also reflect a disinhibition of the central, parietal and right temporo-parietal regions

to enhance general attention and further monitor sensorimotor information integration for which these regions are critical (Babiloni et al. 2011; Bzdok et al. 2013; Del Percio et al. 2011; Krall et al. 2015; Mars et al. 2012). Finally, the reduction of high-alpha connectivity may reflect a widespread disinhibition of the fronto-centro-temporo-parieto-occipital network resulting in a large-scale recruitment of specific cognitive and sensorimotor task-related processes provided by these multiple cortical regions (also illustrated by a widespread reduced high-alpha power as described in Shaw et al. 2018) to overcome an elevation in cognitive–motor task demands. Taken together, the observed increase of alpha connectivity may represent a disinhibition of targeted regions, thus elevating their engagement to further recruit sensorimotor as well as general and task-specific attentional resources. A greater recruitment of these particular resources would collectively contribute to an elevation of mental workload in an effort to maintain performance when facing enhanced cognitive–motor demands (Hancock and Warm, 1989; Wickens 2002, 2005, 2008; Young et al. 2015).

Limitations, conclusions and future work

While the work presented here was a first step to investigate functional connectivity underlying changes in mental workload during dual-task walking, this effort included several limitations. The first limitation was the sample size considered in the current work. Future work could employ a larger population to confirm the findings presented here. Second, only the changes in the magnitude of functional connectivity were evaluated. Future work could assess the directional flow of cortico-cortical communication to provide further detail of the cortical dynamics underlying changes in mental workload during dual-task walking. Finally, as with all mobile EEG investigations, it can be difficult to fully reject motion artifact. Motion artifact may have potentially biased the underlying cortical dynamics of mental workload and thus interfered with our results and their interpretation (Castermans et al. 2014; Gwin et al. 2010; Kline et al. 2015; Nathan and Contreras-Vidal 2016; Wagner et al. 2012). However, there are several arguments to suggest that the cortical dynamics observed in this study were not primarily the result of motion-related artifact, but were reflective of underlying cognitive–motor mechanisms. The current effort was not intended to examine the underlying cortical dynamics of specific locomotor events (e.g., heel strike, leg motion), but aimed to investigate the underlying cognitive–motor processes of mental workload during dual-task walking. As such, the likelihood of motion-related artifact biasing data processing and subsequent interpretation is limited since the gait cycle was not synchronized to the cognitive task (Kline et al. 2015). Furthermore, the EEG signals were pre-amplified and secured shielded cables

were employed in the present investigation, which limited the influence of motion-related artifacts (Kline et al. 2015; Nathan and Contreras-Vidal 2016; Reis et al. 2014). Additionally, the method employed here to analyze functional connectivity (i.e., WPLI) has been shown to be fairly robust to noise and thus limited its influence on the detection of the cortical dynamics (Vinck et al. 2011).

Keeping in mind these limitations, it appears that the observed enhanced fronto-centro-temporo-parietal theta connectivity and attenuated inhibition of fronto-centro-temporo-parieto-occipital alpha networking reflect the need to further recruit attentional, working memory sensory/sensorimotor integration resources. The increase of these multiple cognitive–motor resources would result in an elevation of mental workload in an effort to maintain performance in response to an elevation of cognitive–motor challenge due to either a change in task conditions or an increase in difficulty of the secondary task. The reduction of alpha connectivity due to increased cognitive–motor task demands reported here is consistent with previous work (Dai et al. 2017; Nikolov 2013; Sauseng et al. 2005; Siegel et al. 2008), but is also at odds with numerous cognitive–motor studies which revealed opposite findings (Deeny et al. 2003, 2009; Gentili et al. 2015; Rietschel et al. 2012; Teel et al. 2014). Thus, the findings reported here suggest that the proposed mechanisms for the alpha bandwidth may be somewhat specific to the dual-task walking condition participants performed in the current study (Doesburg et al. 2009; Babu Henry Samuel et al. 2018). It is of interest to note that the theta and alpha connectivity were more sensitive to changes in task conditions (representing a substantial modification of motor demand) and in the level of challenge of the secondary cognitive task (resulting in a significant variation of cognitive demand), respectively. However, the mechanisms underlying such sensitivity remains unclear since large networks including multiple functions were identified. Also, as in many dual-task studies, it is challenging to tease apart the cognitive and motor mechanisms. In particular, it is difficult to ascertain whether the observed EEG dynamics in the dual-task walking condition reflect a change in the recruitment of cognitive resources for locomotor control or the performance of the concurrent cognitive task. While both the traditional and comprehensive graph theory-based montages revealed similar alterations in theta and high-alpha connectivity, the latter approach captured additional changes in low-alpha cortical networking dynamics and was computationally more robust since it identified changes in cognitive–motor demands through the modulation of a set of connections forming a network. The role of such cortical connectivity during dual-task walking, as well as other tasks under various cognitive–motor challenges, should be further examined by EEG studies. The understanding of these functional connectivity measures to assess the sensorimotor,

attentional and working memory processes has the potential to inform cognitive–motor mechanisms underlying mental workload in uninjured individuals and, possibly, in patients with limb loss employing prostheses during cognitive–motor performance under various demands.

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interests. The views expressed in this manuscript are those of the authors and do not reflect the official policy of the Department of Army, Navy, Air Force, Department of Defense, or U.S. Government. The identification of specific products, scientific instrumentation, or organizations is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the author, DoD, or any component agency.

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