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Cognitive-motor dual-task interference: a systematic review of neural correlates.

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Highlights

- CMi refers to the simultaneous performance of a cognitive and a motor task as DT

- CMi is assessed by various techniques able to measure the related brain activity

- fMRI studies showed additive/over-additive brain activity as multiple resources are needed

- Specific loci have been identified, although they may depend on the single components

Abstract

Cognitive-motor interference refers to dual-tasking (DT) interference (DTi) occurring when the simultaneous performance of a cognitive and a motor task leads to a percentage change in one or both tasks. Several theories exist to explain DTi in humans: the capacity-sharing, the bottleneck and the cross-talk theories. Numerous studies investigating whether a specific brain locus is associated with cognitive-motor DTi have been conducted, but not systematically reviewed. We aimed to review the evidences on brain activity associated with the cognitive-motor DT, in order to better understand the neurological basis of the CMi. Results were reported according to the technique used to assess brain activity. Twenty-three articles met the inclusion criteria. Out of them, nine studies used functional magnetic resonance imaging to show an additive, under-additive, over- additive, or a mixed activation pattern of the brain. Seven studies used near-infrared spectroscopy, and seven neurophysiological instruments. Yet a specific DT locus in the brain cannot be

concluded from the overall current literature. Future studies are warranted to overcome the shortcomings identified.

Keywords: cognitive-motor interference; dual-tasking; dual-task interference; neural correlates; neuroimaging; neurophysiology

Introduction

The concurrent performance of a cognitive and motor task yields to a different pattern of interference. This includes four major isolated changes (motor task facilitation, motor task interference, cognitive task facilitation, and cognitive task interference), or the possible combinations of these observations, as well as no changes at all. Therefore totaling nine potential pattern of interferences (Plummer, Eskes et al. 2013). Dual Task (DT) interference (DTi) occurs when the simultaneous performance of two different tasks results in the deterioration in one or both task performances. As a specific kind of DTi, the cognitive-motor interference (CMi) occurs when the DT paradigm includes a motor task (i.g., walking) and a cognitive task (i.g., counting numbers backwards). During the DT performance, any modification from the reference single task (ST) condition in one or both subtasks is measured mostly as a percentage of change. This is also known as a DT cost (DTC) (Friedman, Polson et al. 1982). Whenever one or both of the performed ST(s) will change in a DT condition, a CMi will likely be present.

The underlying mechanisms of the DTi are still unclear. They have been described as a competition for attentional resources (Wickens 1980) or a competition for information-processing neural pathways (Pashler 1994). Three are the most influential "attentional" theories accepted to explain the CMI in humans: 1) the central capacity sharing model postulates that DTi is caused by a capacity limited

process that can allocate capacity in a graded fashion or, in other words, when people perform two tasks simultaneously, resources must be re-distributed between the tasks (Friedman, Polson et al. 1982); 2) the bottleneck model, which is based on the idea that certain critical tasks must be carried out sequentially (and not in parallel), therefore a bottleneck arises when the information from two different tasks are processed by similar neural processor or networks (Pashler 1994); and 3) the cross-talk model which suggests that if two tasks are from a similar domain and use the same neuronal populations, they will not disturb each other (Navon and Gopher 1979; Navon and Miller 1987); therefore such a kind of facilitation will come up when two tasks are from domains using similar pathways.

In the case of a DT involving walking as the motor task, every gait modification (such as slowing down) should be interpreted as an increase in cost for the involvement of cortical attentional processes while walking. More direct evidence of the correlation between cortical brain activation and a DT performance during walking have been shown in the last years, by the means of innovative instruments (e.g. near-infrared spectroscopy-NIRS, Mobile Electroencephalography). They are able to overcome the portability limitations of the conventional neuroimaging technologies. Besides walking, DT paradigms may involve many types of motor tasks, including upper limb movements to be simultaneously performed with a cognitive task.

DT performance also requires challenging attentional capacities (specifically the ability to divide the attention) and the integrity of the executive functions (Yogev-Seligmann, Hausdorff et al. 2008). Executive functions refer to higher cognitive processes (e.g. volition, planning, purposive action, action monitoring, and cognitive inhibition) that use and modify information from many cortical sensory systems. This occurs in the anterior and posterior brain regions to modulate and

produce effective, goal-directed actions and for the control of attentional resources (Lezak New York 1995).

A great number of studies have been conducted in neuropsychology to understand the basis of DT and divided attention capacity in humans; but most of them applied a double cognitive task. More recently, fewer studies have been done to understand the neural correlates of CMi (using a DT paradigm involving a cognitive and a motor task), by the means of more advanced techniques (i.g. functional magnetic resonance imaging – fMRI, fNIRS). So far no paper has been published to provide an updated revision of the evidence available in literature on the neural correlates of cognitive-motor DT. With this paper we aimed to systematically review the studies conducted to reveal the neural correlates of cognitive-motor DT. We grouped findings according to the technique used to detect the brain related activity and by comparing the results with those available on cognitive-cognitive DT.

Methods

Inclusion criteria

We included all types of studies investigating the effect of performing a cognitive-motor DT on brain activity in healthy subjects. Brain activity had to be measured by neuroimaging techniques (fMRI, fNIRS, positron emission tomography – PET) or neurophysiological instruments (event-related potential – ERP, electroencephalography – EEG, magnetoencephalography - MEG). We excluded (a) studies which applied DT with similar task components, such as cognitive-cognitive and motor-motor DT, (b) studies including healthy subjects that only served as control of persons with any neurological disease, (c) studies investigating attention shifting, (d) studies investigating the effects of training, exercise intervention, therapy, drugs, or alcohol effects on DT and (e) non-English published studies.

Search strategy

The database PubMed was searched up to 1st of November 2015. Search strategies included the following keywords: (cognitive-motor interference OR "dual-task*" OR DT) AND (functional resonance magnetic imaging OR fMRI OR event-related potential OR ERP OR electroencephalography OR EEG OR magnetoencephalography OR MEG OR spectroscopy OR NIRS OR Positron Emission Tomography OR PET) AND (neural correlates OR brain activation OR brain activity), NOT (attention shifting OR practice OR training OR exercise OR intervention OR therapy OR drugs OR alcohol effects on DT). Inclusion and exclusion criteria were applied. Additionally, the reference lists of the included articles were checked for any additional relevant articles. The PRISMA flow diagram of the study selection process is illustrated in figure 1.

The following data were extracted and reported in table 1: participant characteristics (number of subjects, age), single motor and cognitive tasks performed in the task paradigm, type of imaging technique used, clinical outcome, the neural correlates associated with the DT, and the anatomical brain locations (MNI co-ordinates, Talairach co-ordinates and Jülich co-ordinates) of the activated areas related to DT.

Results

The literature search identified a total of 23 articles, which met the inclusion criteria; all articles measured the behavioral and neural activity changes. (Gruber 2001; Matthews, Garry et al. 2006; Just, Keller et al. 2008; Matthews, Martin et al. 2009; Serrien 2009; Gazes, Rakitin et al. 2010; Remy, Wenderoth et al. 2010; Holtzer, Mahoney et al. 2011; Van Impe, Coxon et al. 2011; Johnson and Shinohara 2012; Doi, Makizako et al. 2013; Johannsen, Li et al. 2013; Mandrick, Derosiere et al.

2013; Ohsugi, Ohgi et al. 2013; Wu, Liu et al. 2013; Beurskens, Helmich et al. 2014; Blumen, Holtzer et al. 2014; De Sanctis, Butler et al. 2014; Meester, Al-Yahya et al. 2014; Mirelman, Maidan et al. 2014; Nijboer, Borst et al. 2014; Kwon, Lim et al. 2015; Malcolm, Foxe et al. 2015).

insert figure 1 here

Out of the 23 included studies, 11 applied motor tasks involving the upper limb, 10 involved the lower limbs (mostly walking), and one involved a complex visual-motor task (driving scenario), and one involved an oculomotor task (see table 1). Regarding the cognitive task applied, seven studies used an arithmetic task, five used a visual-based attention task, seven used a working memory task, two used a response-inhibition task, and two used language-related tasks (see table 1).

Brain activity during cognitive-motor DT

In the following paragraphs we report on the main results of the cognitive-motor DT-related neural activity. We decided to report on the main results by grouping studies according to the technique used to measure DT-related brain activation: 1) fMRI; 2) fNIRS and 3) other neurophysiological tools (EEG, MEG, ERP). Brain DT-related activity was measured by the means of different techniques: 9 studies used the fMRI, seven use the fNIRS, and seven used neurophysiological techniques.

Moreover, as previously reported in literature (Nijboer, Borst et al. 2014), the studies which used fMRI were grouped according to the associated neural pattern found in comparison with each ST-related activation: a) over-additive; b) additive; c) under-additive, and d) miscellaneous activations.

1) fMRI studies

fMRI is a functional neuroimaging procedure using MRI technology that measures brain activity by detecting changes associated with blood flow. This technique relies on the fact that cerebral blood flow and neuronal activation are coupled. When an area of the brain is in use, blood flow to that area also increases. The primary form of the fMRI uses the blood-oxygen-level dependent (BOLD) contrast. This is a type of a specialized brain scan which is able to map neural activity by imaging the change in the blood flow (hemodynamic response) across brain cells. The changes in BOLD signals are related to the energy used by the brain cells.

A) Over-additive activation

Over-additive effects can be explained by assuming that the performance of the DT consists of more than the sum of its STs. Such that the brain resources handle additional processes which were not found in either STs, being exclusive to the DT condition. Areas of the prefrontal cortex, as well as parietal regions were implicated as playing an important role in managing the concurrent execution of tasks. Over-additive activation refers also to an over activation of those areas already active during the performance of the component single-tasks (e.g., the prefrontal cortex and cerebellum (Schubert and Szameitat 2003; Wu, Liu et al. 2013).

We found three studies showing extra brain area activation which was associated with performing a DT by fMRI (Van Impe, Coxon et al. 2011; Wu, Liu et al. 2013; Blumen, Holtzer et al. 2014). Two studies involved upper-limb movements (i.g. finger tapping, drawing) (Van Impe, Coxon et al. 2011; Wu, Liu et al. 2013), and one study involved walking (Blumen, Holtzer et al. 2014). Overall and independently from the motor task used, these studies have identified areas of the prefrontal cortex, as well as parietal regions, to play an important role in managing the concurrent execution of two different tasks. Specifically, two studies found an

over-additive activation in areas that were already active during performing the component tasks (e.g., the prefrontal cortex and cerebellum) (Van Impe, Coxon et al. 2011; Wu, Liu et al. 2013). Van Impe et al (Van Impe, Coxon et al. 2011) showed only an up regulation of brain activity in a cluster region involving SMA and pre-SMA (see table 1 for the respective anatomical brain co-ordinates) that was already activated during the ST execution. A specific analysis conducted on these areas showed that both groups were able to upregulate their activity during simultaneous performance of the two tasks. As predicted by capacity sharing models, both age groups were able to be successful at performing the DT because of the available residual capacity in the shared brain resources (Tombu & Jolicoeur, 2003). The authors argued that perhaps under higher task demands, the full capacity of the pre-SMA/SMA would have been reached and serial queuing would have been occurred.

It could also be that the above mentioned regions which was found to be more activated during DT performance, were simply a part of the broader executive control system that manages DT (Collette, Olivier et al. 2005).

Wu et al (Wu, Liu et al. 2013), for the first time, identified two sub-regions of the cerebellum. These were the left lobule V and the right vermis (see table 1 for their anatomical brain co-ordinates), which have been additionally activated during DT execution (which combined a right hand task and a cognitive counting task) compared with STs, suggesting that cerebellum is important in performing dual motor-cognitive tasks (Wu, Liu et al. 2013). They also found that these two identified cerebellar areas were functionally connected to extensive brain networks in the DT condition. In contrast, in the ST (single-tapping or counting task) condition these cerebellar areas only connected to limited brain networks. The authors suggested that when two different tasks were being performed at the same time, the neural networks for each task were being integrated into a single network by a

linkage from distinct brain areas. The ability to integrate and adjust various brain networks is possibly the neural basis that allows performance of multiple tasks at the same time in daily life. In other words, these cerebellar regions are likely parts of executive networks (Buckner et al., 2011). Additionally, their role in dual motor-cognitive task-processing is likely to integrate motor and cognitive networks, and may modify these networks to be more efficient to perform the DT properly.

In their study, Blumen et al. (Blumen, Holtzer et al. 2014) investigated the behavioral and neural correlates of a new imagined gait protocol which involved imagined walking, imagined talking, and imagined walking-while talking. In their second experiment, 33 cognitively-healthy older adults were enrolled to perform the above three imagined conditions in an fMRI. The analysis of neuroimaging data showed a pattern of brain regions that varied as a function of imagery task difficulty (walking>talking>walking while talking), and involved cerebellar, precuneus, supplementary motor and other prefrontal regions (see table 1 for details of anatomical brain co-ordinates).

Additive activation

Additive activation occurs when the percentage signal change in the DT is the summation of activation in the STs (Adcock, Constable et al. 2000; Jaeggi, Seewer et al. 2003; Erickson, Colcombe et al. 2005). Contrary to those studies that find over-additive results, additive activation has been argued to indicate that there are no specific brain regions involved in DT processing. Adcock et al. (Adcock, Constable et al. 2000) implied that interference is the result of an overlap between systems required for each ST: as both STs utilize the same resources (e.g., visual or memory systems), the resource requirements of the DT are the combined requirements of the component tasks. Consequently, the observed DT activation is simply the summation

of the ST activation. Additive effects can also be explained by a time-sharing account, if we assume that access to resources has been integrated perfectly between two processes and that one process does not take away time from the other (Schumacher, Seymour et al. 2001; Salvucci and Taatgen 2008). Time-sharing account was firstly reported from Schumacher et al in 2001, and afterwards formalized in the so called threaded cognition by Salvucci and Taatgen in 2008. Schumacher et al. moved from the idea that DT cost may be an artifact of the priority given to one task. As a consequence, participants might postpone their response to the second task to make sure it is not made before the response on the first task. To test this idea they asked participants to do two tasks in parallel with no order restrictions: a visual– manual task, and an aural–vocal task. Both stimuli appeared at the same time, and the participant was instructed to react as fast as possible on both tasks. The authors found that, given sufficient training, participants achieved perfect time-sharing, enabling them to do both tasks as fast as they would perform each task separately. Time-sharing account is similar to capacity limit theory, but time-sharing only imposes local (resource or region based) limits on activation, but not global ones.

In this group we included only two studies likely fitting with the definition of additive activation (Gruber 2001; Johannsen, Li et al. 2013).

Gruber et al. (Gruber (2001) aimed to re-investigate the functional neuroanatomy of verbal working memory by measuring brain activity during verbal short-term memory tasks under varying task conditions. More deeply, they looked into activity changes associated with the well-established behavioral effect of the articulatory suppression. This effect refers to the decreased verbal short-term memory observed when one has to perform other concurrent articulations, and presumably it is caused by a disruption of the rehearsal mechanism of the

phonological loop (Murray 1968). They applied an interfering condition, which is the above mentioned articulatory suppression and a non-interfering condition, which was an alternating finger movements. The brain activity was measured by fMRI technique, during both ST and DT conditions. They showed that during the non-interfering DT condition with alternating finger tapping, the verbal item-recognition task activated the same cerebral areas: the Broca's area, the left lateral pre-motor cortex, the right cerebellum and the cortex along with the intraparietal sulcus (see table 1 for the respective anatomical brain co-ordinates). This allowed to conclude that DT performance *per se* had no influence on the brain processes that sub-serve verbal short-term memory performances.

Johannsen et al. (Johannsen, Li et al. 2013) investigated the neuroanatomical correlations of adaptive behavioral strategies in cognitive-motor DT when the competition for information processing capacity was severe and might have exceeded individuals' capacity limitations. During the fMRI experiment, participants performed slow continuous, auditory paced bilateral anti-phase ankle dorsi-plantar flexion movements as an element of normal gait at 5Hz in single and DT modes. The secondary task involved a visual, alphabetic N-back task, which randomly occurred in 0- back or 2-back form. Participants' ankle movements were recorded using an optoelectronic motion capture system. The hastening of ankle movements in the DT 2-back condition was negatively associated with activations found in the left inferior frontal gyrus (see table 1 for its anatomical brain co-ordinates). Individuals with less activation of this area were more likely to deviate from the set target pace when concurrently performing the DT 2-back condition. However, the interaction contrasts between the DT 2-back condition and the sum of the two relevant ST conditions in this study did not reveal any emergent DT specific local activations. Among the different reasons hypothesized to explain these results, we quote the following ones:

1) both concurrent tasks were properly executed so that the task-relevant brain regions were sufficient to meet the DT requirements; or 2) the degree of structural interference in cognitive-motor DT is less than in only cognitive DT.

C) Under-additive activation

Under-additive activation indicates that the increase in activity during the DT is less than the sum of the activity in the single task (Klingberg 1998; Just, Carpenter et al. 2001; Newman, Dawes et al. 2007; Buchweitz, Keller et al. 2012). Several theories have been proposed to explain under-additive activation. According to Just and Varma (Just and Varma 2007), there is a limit on the amount of active cortical tissue, which might require the activity to be divided amongst more areas during a DT. In contrast, Anderson et al. (Anderson, Bothell et al. 2011) argued that during multitasking there is competition for cognitive resources between tasks. Thus resulting in one task taking away time on the resource from another task, which leads to an activity that is lower than the sum of the STs.

We found two studies showing under-additive activity (Just, Keller et al. 2008; Remy, Wenderoth et al. 2010). One study applied a bimanual coordination pattern (Remy, Wenderoth et al. 2010), and one applied a driving scenario (Just, Keller et al. 2008). The under-additive activation encountered by Just et al. (Just, Keller et al. 2008) was located primarily in areas related to visual processing when driving was combined with an auditory task. The addition of a sentence listening task decreased the brain activation associated with performing a driving task, despite the fact that the two tasks drew on largely non-overlapping cortical areas. Indeed, activation during DT decreased in bilateral parietal and superior extrastriate secondary visual areas (for the MNI coordinates of the region with the largest cluster of activation during DT relative to the driving alone with fixation, see table 1). A

limitation of this study is that participants did not perform the cognitive task in isolation. Future neuroimaging studies of DT while driving should assess whether activation in the DT condition is truly an under-additive phenomenon relative to the activation found when performing each of the ST(s) in isolation.

Rémy et al. (Remy, Wenderoth et al. 2010) evaluated which regions evidenced a significant interference (either an increase or decrease of activity) when both motor (a complex bimanual task) and a simple visual search tasks were performed simultaneously rather than as STs. They also looked at the effect of learning on the neural correlates. Interestingly, they found that the performance of the motor task was impaired under DT conditions during early learning but not during late learning. This is considered to be a traditional behavioral marker of a shift from an attention-demanding to an automatized performance mode. In early learning, reduction of activity during the DT was observed in lateral frontal and parietal regions accessed by both STs (see table 1 for the respective anatomical brain co-ordinates), which apparently was associated with motor performance impairment. In particular, the middle frontal gyrus may have been critical to optimize completion of the bimanual task in early learning. Once the bimanual pattern was automatized, DT completion was no longer associated with reduced frontal and parietal activity. The authors suggested that DTi in early motor learning occurred because of competition for the same neural resources, i.e. both the primary motor and the secondary task required involvement of frontal and parietal subareas.

D) Miscellaneous of under-, over- and additive activations

Two studies were included in this group, in which a mixed combination of the previous patterns of brain activity may be found (Gazes, Rakitin et al. 2010; Nijboer, Borst et al. 2014).

In their experimental study, Nijboer et al. (Nijboer, Borst et al. 2014) found no indication of regions that correlated exclusively with DT performance in all three DT paradigms used (n-back plus tracking, n-back plus tone counting, and tracking plus tone counting). Instead, they found a mix of under-additive, additive and over-additive activations in different areas (see table 1 for the respective anatomical brain co-ordinates), which is in line with the idea that multitasking activation and interference are dependent on the STs. For example, they found under-additive activation primarily in areas used by just one of the two STs (the superior temporal gyrus for the ST tone-counting, or the supraparietal lobule and the inferior temporal gyrus for the tracking ST). They suggested the time-sharing theory to account for this. As the whole time has to be shared between tasks, resources required by a ST can thus be accessed less frequently, leading to a smaller gain in activation. Furthermore, under-additive activation was also found in the pre-SMA area. Additive activation was revealed in frontal regions such as the dorso-lateral prefrontal cortex and the ventro-lateral prefrontal cortex. Additive behavior would imply efficient integration between tasks for these two regions. In turn, that would indicate that either ST does not tax these regions continuously. In this case, as the tone-counting and the 2-back tasks both have time between subsequent stimuli, the tasks are not continuous, and processing primarily occurs at discrete intervals. Therefore, it is plausible that these regions are not used continuously while processing these tasks. For example, if the amount of information retrieved during the dual task is the sum of what is retrieved during the single tasks, it would be expected to see an additive behavior in the dorso-lateral prefrontal cortex. This means that retrieving information from the declarative memory is not a continuous process, and is only required at the presentation of a new stimulus. Over-additive activation seems to be the case of the 2-back plus tracking condition, which adds a new process to the task in order to

manage the switching of attention between two screen areas, as well as switching between hands for the correct input. Thus, this attention-switching process only occurs in the DT, leading to an over-additive effect on activation. This over-additive behavior was found primarily in the cerebellum, an area that is important for visuomotor control.

Gazes et al. (Gazes, Rakitin et al. 2010) found decreased activation in DT compared to ST performance in regions associated with the motor task and an increased activation in frontal regions associated with attention regulation. The decreased brain activity in the left primary motor cortex (see table 1 for the respective anatomical brain co-ordinates) was likely related to the worsened tracking performance. The simultaneous increased activation in regions associated with the bottom-up attention system (see table 1 for the respective anatomical brain co-ordinates) was suggested by the author to resolve the conflict between the two tasks. The suggestion was by a re-orientation of attention to the target stimuli, which was assigned a higher processing priority due to its rare occurrence compared to the continuous tracking task. This study provided evidence for a DT conflict resolution by the bottom-up attention system. The mechanism is based on the driving role of the external stimuli on attention orientation. Whereas the top-down mechanism is essential for the internal control of orientation guided by goals, it is also embodied in the activation of the dorsal attention system. The target stimulus onset most likely triggered the ventral attention system, engaging and re-orienting attention whenever a target stimulus was presented.

2) fNIRS studies

fNIRS is the use of NIRS for the purpose of functional neuroimaging. The NIRS is an optical imaging method that measures the change of concentration in both

oxygenated and deoxygenated hemoglobin (HbO2 and HHb, respectively). It also appears suitable to assess the relationship between cortical activation and hemodynamic response.

Five studies were found to apply NIRS to detect DT-related brain activity. However, they compared brain activity during a DT with the brain activity during the motor ST only, therefore we lack information about the activation during the cognitive ST (Holtzer, Mahoney et al. 2011; Doi, Makizako et al. 2013; Ohsugi, Ohgi et al. 2013; Meester, Al-Yahya et al. 2014; Mirelman, Maidan et al. 2014). All studies involved lower limb movements in terms of walking or standing (Holtzer, Mahoney et al. 2011; Doi, Makizako et al. 2013; Ohsugi, Ohgi et al. 2013; Meester, Al-Yahya et al. 2014; Mirelman, Maidan et al. 2014).

The study of Holtzer et al. (Holtzer, Mahoney et al. 2011) was the first one to show an increase of oxygenation levels in the prefrontal cortex during walking while talking compared with normal walking. The prefrontal cortex activation was bilateral and the oxygenation level was higher in younger subjects, suggesting that older adults may under-utilize the prefrontal cortex in attention demanding locomotion tasks.

More recently, Mirelman et al. (Mirelman, Maidan et al. 2014) used the NIRS to examine whether brain activity during DT walking was specific for either the verbalization component of the cognitive task or for the walking. They showed that DT walking (not standing) was associated with frontal brain activation and that the observed changes were apparently not a response to the verbalization of words (articulation speech) but were related to the cognitive load during gait. Indeed, the more attention demanding cognitive task applied (subtracting by 7) compared with only counting numbers forward was highly inversely correlated to HbO_2 levels. Hence, those who performed less may need to recruit more cognitive resources to

perform the task. In contrast, the cognitive task of subtraction did not correlate to oxygenation levels during the standing condition, perhaps because standing is a simpler, less complex motor task than walking (Mirelman, Maidan et al. 2014).

Beurskens et al. (Beurskens, Helmich et al. 2014) used NIRS to detect changes in the frontocortical hemodynamic during two different DT of walking paradigm (one during a checking task and one during talking). Their findings partly confirmed previous accounts on higher DTCs in stepping parameters (e.g. decreased step duration) in old age, particularly with a visual task and negative DTC (e.g. improved performance) during the verbal task in young adults. Functional imaging data revealed little change of prefrontal activation from single- to DT walking in young individuals. In the elderly, however, prefrontal activation substantially decreased during DT walking with the complex visual task. The authors suggested a shift of processing resources from the prefrontal cortex to other brain regions when seniors face the challenge of walking and concurrently executing a visually demanding task.

Mandrick et al. (Mandrick, Derosiere et al. 2013) used an isometric grasping contractions as the motor task that was combined with a mental task condition. The DT condition activated the right PFC region that is similar to that of the single motor task (isometric grasping contractions at 15% and 30% of the maximal voluntary contraction). It is noteworthy that a larger change in deoxyhemoglobin was observed in DT conditions reaching borderline significance (p = .051) compared to the motor tasks alone.

3) Neurophysiological studies

Three studies used EEG (Matthews, Garry et al. 2006; Matthews, Martin et al. 2009; Serrien 2009), one used cortico-muscolar coherence measures (CMC MEG-EEG)

(Johnson and Shinohara 2012), one used the simultaneous recording of EEG and MEG (Kwon, Lim et al. 2015) and two used the mobile brain/body imaging technique (MOBI) (De Sanctis, Butler et al. 2014; Malcolm, Foxe et al. 2015).

Two studies involved upper-limb movements (e.g. finger tapping, drawing) (Matthews, Garry et al. 2006; Matthews, Martin et al. 2009; Serrien 2009; Johnson and Shinohara 2012), two involved walking (De Sanctis, Butler et al. 2014; Malcolm, Foxe et al. 2015) and one used ocular movements (Kwon, Lim et al. 2015).

Matthews et al. (Matthews, Garry et al. 2006; Matthews, Martin et al. 2009) investigated brain activation during the DT compared with the ST activity (a bimanual coordination task and a reaction time based visual task) by means of the EEG. In both studies, they found that young people showed an overall significant reduction in P3a amplitude under both DT conditions relative to the ST condition. In this earlier study (Matthews, Garry et al. 2006) the observed reduction in P3a amplitude under DT relative to the ST condition could indicate an overlap in resources related to the automatic contextual processing of stimuli by the two tasks being performed. The further reduction in P3a amplitude when the motor task was prioritized was related to the possibility that automatic contextual resources are also affected by the voluntary allocation of attention to the bimanual coordination task.

In the study of Serrien (Serrien 2009) the neural dynamic was assessed by means of the EEG coherence in the beta frequency band (13–30 Hz) and included intrahemispheric, interhemispheric and midline connectivity profiles. The authors showed that coherence intensified across the motor network during DT for unimanual tapping, which permitted to preserve performance. For bimanual tapping, strengthening of functional connectivity was not observed for interhemispheric and midline regions, which associated with a degradation of coordinative output. The latter underlines the significance of these communication pathways for bimanual

behaviour. Overall, the findings indicate that dynamic modulation of functional connectivity pattern provides a substrate for preserving behaviour in effortful circumstances such as dual tasking.

Johnson et al. (Johnson and Shinohara 2012) compared corticomuscular coherence between young and elderly adults during the performance of a unilateral fine motor task and concurrent motor and cognitive tasks. Peak corticomuscular coherence between the electroencephalogram from the primary motor cortex and surface electromyogram from the first dorsal interosseous muscle was compared during steady abduction of the index finger with visual feedback. In the alpha-band (8–14 Hz), corticomuscular coherence was greater in elderly than young adults especially during the motor-cognitive task. It is noteworthy to remember that alpha-band (8–14 Hz) corticomuscular coherence is not dominant during motor tasks, but significant peaks have been observed within the alpha-band in some motor tasks requiring a distribution of attention to the task. The beta-band (15–32 Hz) corticomuscular coherence (the greatest part of oscillatory activity for motor task is within this band) was higher in elderly than young adults during DT. In addition, beta-band corticomuscular coherence in the motor-cognitive task was negatively correlated with motor output error across young but not elderly adults, suggesting that individuals with greater beta-band corticomuscular coherence may exhibit more accurate motor output in young, but not elderly adults, during DT.

Kwon et al. (Kwon, Lim et al. 2015) tested whether a DT can be differentiated in the neural and behavioral responses of healthy subjectswith varying degree of working memory capacity. They combined word recall and oculomotor tasks because they incorporate common neural networks including the fronto-parietal (FP) network. Three different types of oculomotor tasks were combined with two memory load levels for a word recall task. The authors measured oscillatory brain

activity with simultaneous MEG and EEG recordings. Prominent frontal midline theta (4–6 Hz) synchronization emerged in the EEG of the group with high working memory capacity during the early phase of the high-load DT condition. Conversely, significant parietal upper alpha (10–12 Hz) desynchronization was observed in the EEG and MEG of the group with low working memory capacity during the same period (Kwon, Lim et al. 2015). The authors concluded that specific brain oscillations may reflect different strategies for allocating cortical resources during combined word recall and oculomotor DT.

Finally, two studies used the MoBI technique that integrates high-density ERP recordings with simultaneously acquired foot-force sensor data to monitor gait patterns and brain activity concurrently.

De Sanctis et al. (De Sanctis, Butler et al. 2014) showed differences in neural processing associated with inhibition between sitting and walking conditions. Specifically, they found no visual evoked potential differences between sitting and walking, which indicated that sensory-perceptual processing stages of the inhibitory task were not affected by the walking load. Their results indicated that DT load targets specific processing stages of the inhibition task. They found robust differences in amplitude, latency and scalp distribution of the ERP components associated with inhibitory functioning between sitting and walking, suggesting an alteration of the neuro-cognitive processing under increased task loads.

More recently, Malcolm et al. (Malcolm, Foxe et al. 2015) utilized the MOBI technique to assess the effects of motor load on cognition in young and elderly healthy subjects. They compared behavioral and ERP measures associated with performing a Go/No-Go response inhibition task as participants sat down (stationary sitting) or walked on a treadmill. They found that older, but not young adults' accuracy dropped significantly when performing the inhibitory task while walking.

Older subjects showed a relative delay and attenuation of ERP modulations that accompanied the behavioral costs. The authors then suggested that this finding might indicate an age-associated loss in flexible resource allocation across multiple tasks.

insert table 1 here

Discussion

This systematic review demonstrated that multiple studies investigated the neural correlates of the cognitive-motor DT. Different techniques have been used across these studies, hampering direct comparisons among them. A high number of studies used fMRI and they also yielded different results. The majority showed an over-additive activation of brain areas during DT performances, while others found only additive activation or under-additive activation effects of DT performance.

The over-additive activation was found either in areas already activated during the ST, hence being task-dependent (e.g. the prefrontal cortex and the cerebellum) in extra-areas that were not previously activated during the ST performance. The findings of areas already activated during ST should imply that interference is the consequence of task interactions in several brain regions as multiple bottlenecks (De Jong 1993) would exist. The findings of extra brain areas that have been shown to be additionally activated in a dual- but not in single STs (see bilateral precuneous, parietal and prefrontal cortex) would suggest the existence of a locus for DTi in brain areas also related with executive functions and the top-down attention system. Moreover, even the cerebellum has been found to be activated as an extra area during a DT, suggesting its relevance in the coordination of cognitive-motor DT.

The seminal neuroimaging based study using fMRI to explore which cerebral areas were activated during cognitive-cognitive DT performance was conducted by

D'Esposito et al. (D'Esposito, Detre et al. 1995) in 1995. In this study the authors used a DT paradigm including two cognitive task, as commonly used in neuropsychology studies in humans. The comparison of the dual- to the ST conditions showed significant increasing of activity bilaterally in the dorsolateral prefrontal cortex (BA 9 and 46) and the anterior cingulate region. This supported the hypothesis that specifically the dorsolateral prefrontal cortex is involved in the allocation and coordination of attentional resources, as a specific locus of DTi. Afterwards other studies did no confirm this finding. Collette et al. (Collette, Olivier et al. 2005) did not observe activity limited to the dorsolateral prefrontal cortex but in a larger antero-posterior cerebral network during a DT. Adcock et al. (Adcock, Constable et al. 2000) suggested that DT coordination may be intermediated by interactions between anatomically and functionally distinct systems engaged in executing STs, as opposed to the hypothesis of an exclusive dorsolateral prefrontal cortex activity dedicated to a generic executive system. In addition, the results of Klingberg et al. (Klingberg 1998) also seem to indicate that no specific cortical area could be associated with any specific cognitive process for DT performance and that DT coordination depends mainly upon interactions between cerebral areas already activated in the ST. Moreover, since the frontal and parietal inferior areas were engaged by the two tasks at the same time, these results are in agreement with the hypothesis that overlapping cerebral activity (as explained by the bottleneck models) is the physiological basis for interference in the DT condition. This hypothesis is furthermore supported by the observation that practice is associated with a decrease in interference between two tasks, as well as decreases in prefrontal and cingulate activity and thus presumably a decrease in overlapping activation (Jenkins, Brooks et al. 1994; Passingham 1996).

Just et al. (Just, Carpenter et al. 2001) further investigated the question of interference between dissociable neural systems. They found that in the DT, the activation in association areas (primarily temporal and parietal cortex) was substantially less than the sum of the activation when the two tasks were performed alone. These results indicate that the simultaneous execution of two tasks requiring non-overlapping cerebral areas is not simply the addictive effect of each task performed alone. Instead, the DT condition induces some mutual constraints among cortical areas.

All taken together, these studies with the exception of D'Esposito et al. (D'Esposito, Detre et al. 1995), demonstrated that DT coordination is not dependent upon the exclusive prefrontal area but rather involves the interplay of various specialized information-processing systems. One possible reason contributing to these divergent findings is the difference in the DT paradigms or in the single motor and/or cognitive tasks used. It is relevant to note here that the lack of specific locus for DTi may be due to the ability of the participants to carry out both concurrent tasks well enough so that the task-relevant brain regions were sufficient to meet the DT requirements. Another possible explanation is the use of different analysis processes of the DT specific brain activation. A comparison of the DT with the sum of the STs, an interaction contrast or a conjunction analysis could have led to different results (for a review see Szameitat AJ et al., 2011) (Szameitat, Schubert et al. 2011). The analysis of DT brain imaging research involves a number of potential complications; one such complication arises from the fact that the absolute values of the data obtained by the means of fMRI or PET (positron emission tomography) cannot be interpreted directly. Therefore, researchers have to resort to relative values obtained by comparing (e.g. contrasting) the activity during the DT performance with some reference activity level. Usually, the DT activity is compared with an activity

derived from the ST component that make up the DT. For instance, the DT activity may be contrasted with the activity of one ST, with the sum of both STs, or with the mean of the two STs. An alternative approach is to compare the DT with a (resting) baseline condition. Critically, the inferences which can be drawn from such comparisons depend on the exact nature of the contrast examined. As outlined above, the interaction contrast has the disadvantage that it includes the resting baseline. To circumvent this problem, one could use a conjunction contrast which does not involve the resting baseline. In order to conduct a conjunction analysis, first the two independent contrasts of the DT are calculated. In the second step, only areas are considered that are active in both contrasts, since such areas are related to the DT-specific component. However, the interpretation of the activations revealed by the conjunction analysis as DT-specific is feasible only if there is no ST-related activation in the activated area(s).

Yet, it may be reasonable to suggest that the degree of structural interference in the cognitive-motor DT is less than in the cognitive only DT.

Future studies employing similar experimental designs are warranted to better investigate the pattern of activation either in healthy individuals or in persons with neurodegenerative disorders. Assessing the neural correlates of DT during walking as well as the connections between motor and cognitive functions during walking in complex situations could lead to the development of new strategies to improve DT abilities. Particularity in neurological diseases, such as Parkinson's disease or multiple sclerosis, where CMi is a common disabling finding which is attributed to risk of falls (Al-Yahya, Dawes et al. 2011).

A better understanding of the neural underpinnings of potential disease-related changes may lead to improved practical clinical implications and/or strategies to reduce fall risk and enhance mobility in aging.

5. *Conclusions*

According to the current attentional theories, CMi during DT performance may be explained by two main theories, the limited attentional capacity sharing and the bottleneck models. The literature available on the neural correlates of DTs suggest that a specific locus for DTi does not likely exist, since the additional brain areas activated across the different studies was dependent from the nature of the single task. Multiple imaging studies have failed to find an additional area specifically involved in DT performance, although there is evidence that for some combination of tasks, prefrontal activation does increase in the DT situation. The main determinant of whether or not multitasking is demanding of executive function may depend on how automatic the two tasks used in the studies are in the first place and whether they draw on the non-overlapping cortical areas. On the other hand, different pattern of increased or decreased activation of task-specific or non-specific neuronal areas have been reported. It is not possible to draw conclusions since the methodological characteristics we reported in Table 1 hinder direct comparison between studies. Studies investigating the neural correlates (e.g. functional MRI, neurophysiology) of DTi in specific neurologic disease are strongly recommended.

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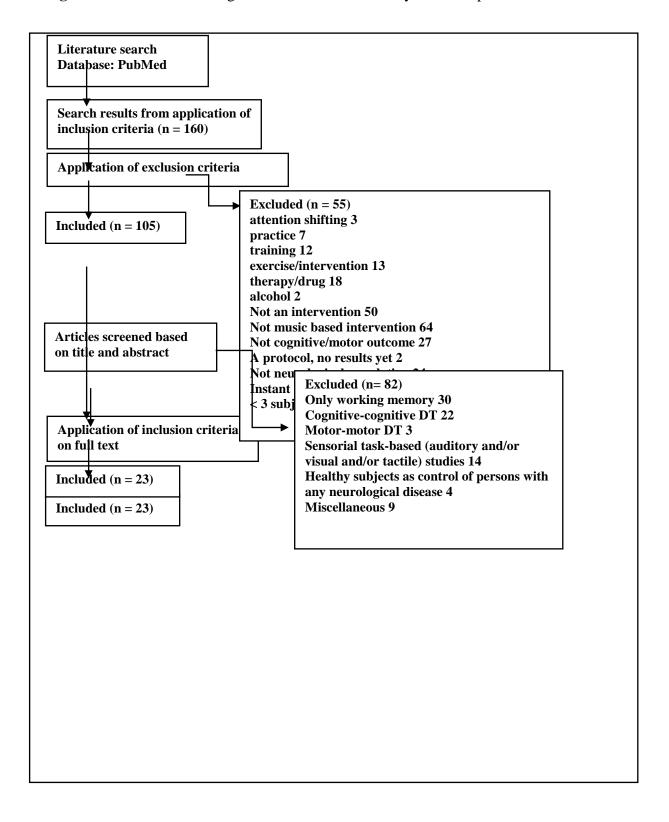**Figure 1.** PRISMA flow diagram to summarise the study selection process.

Literature search Database: PubMed	
Search results from application of inclusion criteria (n = 160)	
Application of exclusion criteria	
Included (n = 105)	**Excluded (n = 55)** **attention shifting 3** **practice 7** **training 12** **exercise/intervention 13** **therapy/drug 18** **alcohol 2** **Not an intervention 50** **Not music based intervention 64** **Not cognitive/motor outcome 27** **A protocol, no results yet 2**
Articles screened based on title and abstract	**Not neurological population 21** **Instant** **< 3 subj**
	Excluded (n= 82) **Only working memory 30** **Cognitive-cognitive DT 22** **Motor-motor DT 3** **Sensorial task-based (auditory and/or visual and/or tactile) studies 14** **Healthy subjects as control of persons with any neurological disease 4** **Miscellaneous 9**
Application of inclusion criteria on full text	
Included (n = 23)	
Included (n = 23)	

Table 1. Overview of sample size, participants, experimental methods and results of studies investigating the effects of cognitive-motor DT on neural activity. Age is reported as mean ± standard deviation (*) or as median (^) or as range values (§).

	Participants n; age	Single motor and cognitive tasks in the DT paradigm	Technique	Clinical Outcome during DT	Neural activity associated to DT (potential underlying mechanism)	Anatomical brain co-ordinates of the activated areas during DT
Gruber et al 2001	11; 24.7 ± 4.3*	MT= alternating finger tapping; CT=verbal working-memory trials	fMRI	No significant changes	No extra-neural activity during DT (CCS model)	Talairach co-ordinates No specific areas, but common activations in: - IFG L (BA 44) -60 8 2 - PeG L -56 0 32 - Cerebellum R 20 -60 -28 - Intraparietal sulcus L/R -40 -40 48, 32 -64 52
Matthews et al 2006	16; 20.3 ± 2.6*	MT=an anti-phase bimanual coordination task (SM); CT=a visual three-stimulus task (SV); motor and visual prioritisation	EEG	RT to visual targets increased when SM was prioritised	Overall significant reduction in P3a amplitude under both DT conditions relative to the ST conditions (CCS model)	n.a.
Serrien et al 2008	9; 21 ± 2*	MT=tapping on a keyboard (a. with right index, b. tapping with left index, c. bimanual); CT= verbal counting adding the digit 2 to a 3-digit integer	EEG	Compared to ST= 1. movement tempo decreased in "c"; 2. counting decreased in all DT(s)	EEG coherence intensified across the motor network during DT for unimanual tapping (CCS model). For bimanual tapping, no increase of connectivity for interhemispheric and midline regions (both CCS and BN model)	n.a.
Just et al 2008	29; 18-25§	MT=simulated driving task; CT=an auditory language comprehension task	fMRI	92% of accuracy level of CT, and more errors and larger deviation from an ideal path for the MT	Decreased activation in bilateral parietal and superior extrastriate secondary visual areas, with the largest decreases found in the right parietal lobe (CCS model)	MNI co-ordinates - Overall, there were found the same areas activated in the contrast of driving alone with fixation - Peak of the largest cluster of activation in R middle occipital gyrus(^): 28 -96 4
Matthews et al 2009	16; 21.7 ± 5*	MT=an anti-phase bimanual coordination task (SM); CT=a visual three-stimulus task (SV)	EEG	Coordination stability was significantly reduced	Overall significant reduction in P3a amplitude under both DT conditions relative to the ST condition (CCS model)	n.a.
Gazes et al 2010	Group 1: 22; 22-33§ Group 2: 34; 18-34§	MT=a visuomotor compensatory tracking task; CT=a visual detection task	fMRI	Increased tracking error and decreased joystick speed	Decreased activation in DT relative to ST in regions associated with tracking (left primary motor and the left somatosensory cortex), and increased activation in anterior insula, ACC, IFG and IPG (BN model)	Talairach co-ordinates - PrG L −38 −24 58 - PrG L −30 −11 54 - PoG L −53 −21 40 (decreased activation) - Insula L −46 4 2 - Insula R 40 −12 1 - CG R (BA 32) 4 23 36 - CG R (BA 24) 6 6 37 - IFG R 36 25 −6

						- IFG L −28 25 −11 - IPG L −25 −48 40 (increased activation)

Rémy et al 2010	12; 23.6 ± 3.6*	MT=a bimanual coordination pattern; CT=a visual search task; pre-and post-learning	fMRI	PRE-learning= motor performance reduced; POST-learning= no changes	Reduction of the activity in lateral frontal and parietal regions involved in both visual search and motor coordination tasks (BN model)
					No extra cortical activity in the DT relative to the sum of the two ST
						MNI co-ordinates
						Overlapping regions (PRE-session) in:
						- Middle PF gyrus R
						  (BA 10) 38, 58, 1
						  (BA 9) 26, 54, 34
						- IFG L −52, 14, −8
						- IFG R 54, 18, −4
						- Superior parietal gyrus L −30, −56, 60

Holtzer et al 2011	Group 1: 11; 19–29§ Group 2: 11; 69–88§	MT=walking; CT=reciting alternate letters of the alphabet	NIRS	Gait velocity reduction. Gait velocity was higher in group 1	Bilateral increased activation levels of PFC; in group 2 the increase in oxygenation levels in the PFC was attenuated (CCS model)	n.a.
Van Impe et al 2011	Group 1: 20; 20.7-32.6§ Group 2: 20; 62.3-76.5§	MT=draw circles by moving a pen over an fMRI-compatible touch panel; CT=mental arithmetic task	fMRI	Mean DTC did not differ significantly from baseline	A cluster on the border of the SMA and pre-SMA was shown to be up-regulated during DT performance in both groups (CCS model)	MNI co-ordinates Border of the SMA and pre-SMA Group 1: −4 −2 64 Group 2: −4 2 62
Johnson et al 2012	Group 1: 16; 23.9 ± 5.8* Group 2: 13; 69.2 ± 4.7*	MT=abduction of the index finger, at different % of MVC force for the right and left side; CT=resolving a trial of 3 mathematical problems and remembering the answers over time	EEG-MEG CMC	The CV of right index force increased by >2 times in group 2; cognitive accuracy decreased by 9%	Alpha-band CMC in the DT was greater in group 2; beta-band CMC was negatively correlated with motor output error in the DT for group 1, but not group 2 (CCS model)	n.a.
Doi et al 2013	16; 75.4 ± 7.2*	MT=walking; CT=a verbal letter fluency task	NIRS	Walking speed was slower compared to ST	Higher oxy-hemoglobin level in PFC during DT compared to ST (CCS model)	n.a.
Johan nsen et al 2013	12; 26.1 ± 4.7*	MT= Bilateral anti-phase ankle dorsi-plantar flexion movements; CT= a visual, alphabetic 0- or 2-back task with presentation rate at .7 Hz	fMRI	During the 2-back DT=changes in movement parameters (average inter-response interval, CoV of absolute asynchrony, SD of peak angular velocity)	The hastening of ankle movements in the DT 2-back condition was negatively associated with activations found in the left IFG (CCS model)	Jülich probabilistic cytoarchitectonic maps - IFG L 40 34 26
Mandr ick et al 2013	15; 28.3 ± 6*	MT=isometric grasping contractions at 15% and 30% of the MVC with non-dominant hand; CT=subtraction of a 2-	NIRS	The % of correct answers declined for the combined task at the 30%	Although a larger change in deoxy-Hb was observed in DT (p = .051), PFC activity did not change significantly as compared to the motor tasks alone	n.a.

		digit number from a 4-digit number for 60 seconds		MVC; the SD of force at 30% MVC was greater	(CCS model)	
Ohsugi et al 2013	Group 1: 20; 26.0 ± 3.6* Group 2: 15; 77.9 ± 5.3*	MT=stepping in place while seated with each foot while counting out loud forward from zero; CT=serial subtractions of 7 beginning with 100	NIRS	The number of steps was significantly lower in group 2	The Oxy-Hb values were significantly increased during both the CT and the DT; during DT, group 2 demonstrated significantly higher Oxy-Hb values than group 1 (CCS model)	n.a.
Wu et al 2013	18; 22-36§	MT=a self-paced tapping task; CT=a visual letter counting task	fMRI	Errors in finger tapping and letter counting	Right cerebellar vermis, left lobule V of the cerebellar anterior lobe and precuneus activation (CCS model)	MNI co-ordinates - Cerebellum, Vermis R 3 −51 −18 - Cerebellum, Anterior Lobe, Culmen, Lobule V L −24 −47 −24 - Precuneus L −4 −57 58
Beurskens et al 2014	Group 1: 15; 24.5 ± 3.3* Group 2: 10; 71.0 ± 3.8*	MT=walking on a treadmill; CT=completing a visual (checking) or verbal-memory (alphabet recall) tasks	NIRS	Negative DTC during the verbal task in group 1; higher DTCs in stepping parameters in group 2	Little change of PFC activation in group 1; negative DTC with verbal task could be explained by cross-talk model. Decreased PFC activation during DT with the visual task in group 2 (CCS model)	n.a.
Blumen et al 2014	33; 73.0^	MT=walking on a 4 x 14 feet course; CT=reciting alternate letters of the alphabet out loud. They were then trained to imagine walking (iW), to imagine talking (iT) and imagine to do both at once (iWWT)	fMRI	-	Increased activity in bilateral PFC regions during DT compared to ST (walking alone) (CCS model)	MNI co-ordinates - Cerebellum (lobule VIIa, crus 1) R/L 30 267 29 - Precuneus R 30 264 40 - Precuneus R 230 267 40 - Superior frontal gyrus (SMA) R 6 14 49 - Thalamus L 215 213 13 - Middle frontal gyrus R 39 35 25 - Thalamus R 9 210 10 - Insula R 39 14 22
De Sanctis et al 2014	18; 21.8-36.1§	MT=3 conditions a) sat in a stationary way, b) walked deliberately c) walked briskly; CT=Go/NoGo response-inhibition task	MOBI	Longer strides in DT	Increased amplitude, latency and topography of ERP components (N2 and P3) associated with inhibitory control during walking conditions (CCS model)	n.a.
Meester et al 2014	17; 27.8 ± 6.3*	MT=walking on a treadmill; CT=backward by 7	NIRS	No difference of H-reflex amplitude and gait variables	Oxy-Hb concentrations significantly increased in the PFC with DT (CCS model)	n.a.
Mirelman et al 2014	23; 24-38§	MT=2 conditions a) standing and b) walking at self-selected speed; CT=serial subtraction of 7	NIRS	Gait speed reduction and gait variability increase. The CT was similar during both DT(s)	Increased brain activation in PFC areas during DT (CCS model)	n.a.

Nijboer et al 2014	20; mean 22.4, 18-27§	MT=a tracking task; CT=2 conditions a) n-back and b) tone-counting	fMRI	2-back plus tracking condition=slowest 2-back RTs, highest error rates; 2-back plus tone counting=larger increase in error distance	No specific multitasking area was found. Different patterns of activation across conditions could be explained by assuming that the interference is a result of task interactions (time-sharing model or multiple BNs)	MNI co-ordinates Underadditive activation in - Superior temporal gyrus L −45 −37 13 (b) - Supraparietal lobule L −21 −55 61 (b) - Inferior temporal gyrus 54 −70 −2 (b) - pre-SMA 0 −1 52 (a) Additive activation in - DLPFC L −51 2 31 (a) - DLPFC R BA 10/46: 36 38 31 (a) - DLPFC R BA 9/46 45 2 34 (a) Overadditive activation in - Cerebellum 0 −67 −20 (a) - Cerebellum 18 −55 −23 (b)
Kwon et al 2015	17; 23.4 ± 2.7*	MT=oculomotor task composed of a smooth pursuit eye movement (P-SPEM and R-SPEM) task and an eye fixation (Fix-EM) task; CT= word recall task of varying cognitive load (5 or 10 words);	Simultaneous recording of MEG and EEG	Word recall performance in the R-SPEM condition was significantly higher than that in the Fix-EM condition.	Prominent desynchronization patterns in the upper alpha band (10–12Hz) in the parietal area during the P-SPEM condition (only in the low-WMC group performing the high-load task). Significantly higher FM-theta power in the high-WMC group experiencing the random SPEM with the high-load condition (CCS model)	n.a.
Malcolm et al 2015	Group 1: 18; 27.2 ± 4.6* Group 2: 18; 63.9 ± 4.0*	MT=walking at 5km/h speed for group 1 and at preferred speed for group 2; CT=speeded visual Go/No-Go paradigm	MOBI	Significant reduction of accuracy (group 1)	In group 1, ERP modulations at relatively early and later stages were found as motor load increased while walking. Group 2's ERP modulations were limited to later processing stages of the inhibitory network (CCS model)	n.a.

Abbreviations

DT=dual task, ST=single task, MT=motor task, CT=cognitive task, fMRI=functional Magnetic Resonance Imaging, CCS=central capacity sharing, IFG=inferior frontal gyrus, L=left, BA=Broadman area, PrG=precentral gyrus, R=right, n.a.=not applicable, EEG=electroencephalography, RT=reaction time, BN=bottleneck, MNI=Montreal Neurological Institute, ACC=anterior cingulate cortex, IPG=inferior parietal gyrus, PoG=postcentral gyrus, CG=cingulate gyrus, NIRS=near infrared spectroscopy, PFC=prefrontal cortex, SMA= supplementary motor area, CMC=corticomuscolar coherence, CV=coefficient of variation, SD=standard deviation, Hb=haemoglobin, MOBI=mobile brain/body imaging, ERP=event-related potential, DLPFC=dorso-lateral PFC, MEG=magnetoencephalography.

(^): contrast between driving with listening and the fixation baseline