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**Abstract**

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**Keywords** Keywords: gait; posture; dual task; attention.



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# The Interaction between Cognition and Motor Control: a Theoretical Framework for Dual-task Interference Effects on Posture, Gait Initiation, Gait and Turning.

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## Abstract

Studies of dual tasks (i.e. situations during which an individual performs two tasks simultaneously) and the subsequent inter-task interference have shown that locomotion and posture involves motor and cognitive components. Dual tasks therefore constitute a promising avenue for improving the diagnosis, prevention and management of falls or cognitive impairment in populations at risk. However, tackling these major public health concerns with dual-task interventions requires a better understanding of the mechanisms underlying dual-task interference. In this context, we review (i) the main dual-task theories proposed to date and (ii) the factors that can influence dual-task interference effects in healthy young individuals and might therefore explain the current lack of consensus on the mechanisms of dual tasks. We also consider cognitive-motor dual tasks in which the motor task is a less frequently studied transition movement (such as gait initiation or turning), rather than only the often-studied gait and posture tasks. In general, the review focuses on the behavioral effects of dual tasking.

Keywords: gait; posture; gait initiation; turns; dual task; attention.

Short running title: Theoretical Framework for Cognitive-motor Dual-task Interference Effects

## Introduction

Gait was long considered to be a fully automatic task. However, it is now clear that cognition and motor control interact extensively. Indeed, in everyday situations with a variable degree of complexity, healthy older adults and patients with neurodegenerative diseases may present gait impairments that may even lead to falls. Healthy younger adults also change the way they walk (with regard to direction or speed, for example) when adaptation is necessary. Importantly, situations in everyday life often involve cognitive-motor dual tasks, e.g. walking while talking, texting on a cell phone, or thinking about one's shopping list. Consequently, the assessment of cognitive-motor dual tasks is of great interest for gaining a better understanding of cognition/motor control interplay and for improving the diagnosis, prevention and management of cognitive impairment and falls.

### Definition of a dual task and its relevance in scientific studies

Dual-tasking (DT) situations (and especially cognitive-motor dual tasks) are common in everyday life. McIsaac et al. (2015) defined DT as "the concurrent performance of two tasks that can be performed independently, measured separately and have distinct goals" [53]. Dual tasking can lead to a change in performance of the primary task (relative to single-task performance); this change corresponds to the cost of carrying out a second task concurrently and is termed "dual-task cost" (DTC) or, more generally, "dual-task effect" (DTE). Indeed, DT does not always result in a cost or a decay in function relative to single-task performance of one or both tasks; it can also lead to a performance benefit in some situations.

It is important to note that despite McIsaac et al.'s proposed operational definition of DT, the use of this terminology is subject to debate. The difference between a dual task and a complex single task with two types of stimuli is not always obvious. For example, McIsaac and colleagues considered (in contrast to most researchers) that carrying a glass of water while walking is a complex single task (with a single action goal: transporting the water) rather than a dual task. McIsaac et al. also addressed the issue of measuring the performance of each task separately because not spilling the water requires postural control in the same way that gait does. Whereas the presence of obstacles, a dynamic base of support, a narrow pathway, visual manipulation of the environment, and even fast speed are commonly accepted in the literature as factors that impair gait and thus only increase the complexity of the motor task without resulting in a dual task, the DT nature of situations with a motor task and cognitive overload is a greater matter of debate. These tasks involve time pressure or emotional or cognitive constraints; e.g. walking in time to a metronome beat, while listening to an emotionally charged sound recording or when responding to external visual, auditory or somatosensory cues. In view of these disagreements over DT terminology, the present review will adopt McIsaac's definition of a dual task (with the exception of walking while carrying a glass of water, which we include in the dual-task category). Indeed, this paradigm is widespread and frequently studied in the dual-task literature. It can be perceived as involving two tasks with distinct goals (walking forward without falling, and holding a cup of water without spilling it) and separate assessment measures (i.e. various gait parameters, and the level of water remaining in the glass after a certain time). Depending on the characteristics of the study population, not spilling the water while walking will be associated with differing degrees of difficulty and automaticity (i.e. low or high levels of cognitive demand), and DTEs may or may not be observed. Indeed, carrying a tray with four glasses full of water will be totally automatic when performed by a waiter but will require much attention from older adult subjects with balance disorders or from patients with neurodegenerative disease [87].

In the particular case of a walking-cognitive dual task, Yogev-Seligmann et al. (2008) reported that walking under DT situations always leads to deterioration in one or both task performances (the extent of which depends on the task and the population's age or disease status) - except when the cognitive demand is very low [110]. Yogev-Seligmann et al. therefore concluded that gait requires attention (the ability to divide attention, specifically) even in healthy adults with intact locomotor and cognitive functions. Otherwise, the simultaneous execution of an additional attentional task would not affect gait or task performance. On the same lines, DTCs usually increase as gait becomes less automatic - such as in older adults and patients with Parkinson's disease [110]. Lastly, an association between gait and executive function (EF) has also been demonstrated, as DT performance requires the integrity of EF [110].

With this in mind, one important reason for investigating DT during gait is the dual task's important role as a useful clinical marker of both cognitive impairment and the risk of falls, since DT worsens potential cognitive and gait impairments [61]. Firstly, DT enables researchers to discriminate between older adults with mild cognitive impairment (MCI) or Alzheimer's disease (AD) and age- matched normal controls with regard to significantly different time-related gait parameters [62]. Dual tasking can also distinguish people with MCI from patients with AD [17]. Secondly, Lundin- Olsson et al.'s (1997) seminal DT study found that stopping walking when talking was highly predictive of the risk of falls in frail older adults [50]. Individuals who stopped walking when talking displayed a significantly less safe, slower gait, and had a lower degree of autonomy in activities of daily living. Hence, DT can be viewed as an indirect means of evaluating the automaticity of a primary task by studying the level of performance of a concurrent task [86]. This potential prevention tool is simple and fast to use, does not require any equipment, and thus does not induce any costs. Furthermore, by highlighting the relationship between cognition and motor control and the variation in this interplay with age and disease status, DT can also play a role in rehabilitation [29]. Indeed, DT may help to gain a better understanding of (i) specific associations between gait parameters and executive components, and (ii) the related neural correlates, with an ultimate aim of identifying key targets for therapy.

### Objectives of this review

For the reasons mentioned above, the field of DT has attracted growing interest over the last few decades. Hence, results need to be centralized for a better synoptic understanding of these investigations. However, all the reviews of this field are confronted with the same problem: the heterogeneity of the various populations and DT paradigms studied [2,74,84]. As a consequence, a number of questions regarding DT (such as the mechanisms underlying dual-task interference) still need to be answered– often because of a lack of consistency.

The objective of the present review is to first describe the models of dual-task interference developed to date and then to review the factors found to influence DTEs in studies of healthy young adults. In a novel approach, we shall assess the recent literature on cognitive-motor dual tasks in which the motor task is a less frequently studied transition movement (such as gait initiation or turning) as well as those involving the often-studied gait and posture tasks. In general, the review focuses on the behavioral effects of DT.

A greater awareness of causes of variations in DT results will hopefully encourage researchers to standardize the parameters used in their dual-task studies or at least to report them accurately. These steps would facilitate inter-study comparisons, and thus would probably yield more consistent outcomes and a clearer understanding of the interactions between cognitive functions and motor control.

## The mechanisms underlying dual tasks

Before describing the various theories used to explain interference in cognitive-motor dual tasks, we provide an overview of the cognitive processes involved in concurrent tasks and possible patterns of dual-task interference.

## Concurrent cognitive tasks

Above, we described the proven relationship between motor control on the one hand and cognition on the other hand. Nevertheless, DT paradigms comprise various tasks that assess different cognitive functions; these tasks are often inappropriately compared in the literature. To resolve this problem, Al-Yahya et al. (2011) [2] published a classification that discriminates between cognitive tasks on the behavioral and/or cognitive level. Our modified version of this cognitive task classification is shown in Table 1.

On the basis of this classification, one can see that cognitive-motor dual tasks most frequently studied in the literature involve a cognitive task that requires EF, attention or working memory.

## Executive function, working memory, and attention

Studying attention, EF or working memory in isolation is not easy because all three cognitive processes are closely related.

*Executive function* encompasses the higher cognitive processes involved in the cognitive control of non-routine, goal-directed behaviors. It comprises action initiation, response inhibition, planning, set-shifting, dealing with several sources of information, and response monitoring [5,48,51]. The domain of EF has also been extended to the behavioral changes observed in frontal lesions [90]. Likewise, recent aspects of control functions (such as social cognition, theory of mind, strategic processes in episodic memory, insight, and metacognition) have sometimes been incorporated into the domain of EF [33]. This cluster of functions integrates representational, somatosensory and motor components that modulate and produce behavior [110]. In order to deal with the wide range of processes involved in EF, Miyake et al. (2000, 2012) developed an empirical model of EF's three main components: shifting from one task/mental set to another, updating and monitoring of working memory representations, and inhibiting prepotent responses [58,59]. The three components were shown to be separable while being moderately correlated - supporting a concept whereby the executive system has both unitary and non-unitary components.

*Working memory* can be defined as the ability to temporary store and manipulate the information required for completing complex cognitive tasks, such as language comprehension, learning, reasoning, and planning [6]. This limited-capacity brain system has been extensively studied by Baddeley, and his model of working memory is still widely used today [3-4,7-9]. The model comprises four components: a verbal storage system called the phonological loop, a visual storage system called the visuospatial sketchpad, an episodic buffer (which binds information to form integrated episodes), and a central executive (which coordinates these three slave systems and thus controls and regulates cognitive processes).

*Attention*: van Zomeren and Brouwer (1994) addressed the difficulty of reducing attention to a single definition [113]. According to Kahneman (1973) and Corbetta and Shulman (2002) [22,40], attention corresponds to a cognitive process driven by a dynamic interaction between cognitive and sensory factors and which controls for the level of significance allocated to stimuli. In this context, focusing, selecting and/or inhibiting the available stimuli are the main functions carried out by attention. Attention and its components (sustained, selective, divided, and set-shifting attention) can also be conceptualized as the individual's information processing capacity during the performance of a task [104]. In particular, divided attention can be defined as the ability to perform more than one task at a time [110]. Attention therefore underpins EF in a critical manner.

van Zomeren and Brouwer (1994) [113] developed a multicomponent model that is still widely used in psychology to report on the different subcomponents of attention (Fig. 1). The model is based on Posner's component theory (1971) [78], the selectivity and intensity aspects of attention developed by Kahneman (1973) [40], and the concept of the supervisory attentional system (SAS) developed by Norman and Shallice (1986) [68]. According to van Zomeren and Brouwer (1994), attention is divided into two neuropsychologically distinct dimensions, each of which is associated with a different underlying neural network:

(i) intensity, with alertness and vigilance/sustained attention as its subcomponents;
(ii) selectivity, which covers focused and divided attention [113].

Firstly, an attentional task can be characterized by the intensity of the mental activation it requires. Intensity components of attention consist of tonic alertness (i.e. a relatively stable level of arousal that varies slowly with the organism's diurnal, physiological fluctuations), phasic alertness (i.e. the ability to increase the arousal level in response to a high-priority stimulus), and sustained attention (the ability to maintain attention over a long period of time during which, in the context of vigilance, infrequent response-demanding events arise). Secondly, selectivity allows an individual to orient his/her attention and to ignore irrelevant stimuli on two levels; focused attention takes account of only one stimulus or one dimension of a stimulus (color, size, shape, etc.), whereas divided attention considers at least two stimuli or two relevant stimulus dimensions. Lastly, van Zomeren and Brouwer's attentional model (based on the theory developed by Norman and Shallice (1986)) comprises an executive component (the SAS) that manages attentional resources in complex, novel, non-automated or conflicting situations [68]. The SAS can modulate both the intensity and selectivity dimensions.

*Insert Figure 1 around here*

On these lines, Norman and Shallice (1986) shed light on the existence of two levels of attention [68]. The lower level (contention scheduling) is used to address familiar and automatic situations (i.e. routines), while the higher attentional level (the SAS) is required to deal with more challenging and resource-demanding situations. It is interesting to note the parallel between the latter neuropsychological model and the two distinct brain networks related to attention [22,28]. On one hand, the bilateral "dorsal attention network" (including the dorsal parietal and frontal cortices) may be involved in endogenous (goal-driven) attention with top-down stimuli detection, selection and responses. On the other hand, exogenous (stimulus-driven) attention with bottom-up detection and processing of salient or unexpected stimuli would be based on the right-lateralized "ventral attentional network" that includes the temporo-parietal junction and the ventral frontal cortex. Prefrontal regions of the cortex (i.e. middle and inferior frontal gyrus) are assumed to mediate the functional interaction between these networks because of their demonstrated correlation with both systems [28].

## Patterns of dual-task interference effects

Plummer et al. (2013) described nine potential patterns of interference (relative to single-task performance) during cognitive-motor DT: no interference, cognitive-related motor interference, motor-related cognitive interference, motor facilitation, cognitive facilitation, cognitive-priority trade off, motor-priority trade off, mutual interference, and mutual facilitation (Table 2) [74]. In this classification system, some patterns are more likely than others; overall, variability in patterns of cognitive-motor interference can be explained by the task specificity, individual characteristics, and differences in the measured parameters [74]. For example, Plummer and colleagues' (2013) review of studies in stroke populations found mainly cognitive-related interference and mutual interference patterns but also no interference, motor-related cognitive interference, cognitive-priority trade off and cognitive facilitation patterns in the context of DT involving gait [74]. With regard to balance activities with an additional cognitive task, stroke patients presented various patterns of DT interference, such as cognitive-related motor interference, mutual interference, motor facilitation and no interference. In a different disease area, patients with multiple sclerosis exhibited cognitive-related motor interference and mutual interference during dual-task walking, whereas cognitive-related motor interference, mutual interference, and motor facilitation were possible consequences of postural DT [99].

More recently, McIsaac et al. (2015) supplemented this dual-task interference classification by introducing a new dual-task taxonomy [53]. This classification of dual tasks relies on the characteristics of the tasks and the performer, which lead to the various outcomes described by Plummer and colleagues. In other words, the classification considers each task's level of complexity (i.e. the task's constraints and environmental context) and novelty (i.e. the individual's previous experience with performance of the task). In the future, McIsaac et al.'s taxonomy will probably be expanded to include an index that reflects the similarity of neural structure engagement among tasks; the higher the "similarity index", the greater the putative interference effects.

By improving McIsaac's dual-task taxonomy with the other relevant factors of DT paradigms (reviewed below) and Plummer's classification of DT interference patterns, it should be possible to better understand the specific nature of DT-related interference effects with fewer disparities and uncertainties than at present.

## Dual-task theories

In general, several models have tried to explain dual tasks and their effects in humans. However, there is no consensus on which theory best predicts the effects of DT [47,110]. The most widely accepted theories are summarized below (Fig. 2):

(i) **Capacity sharing theories**: The *central capacity sharing model* [40,54,95] postulates that cognitive-motor interference is caused by a limited-capacity parallel processor that divides resources among to-be-performed tasks. This results in lower capacity for each individual task and so the performance of at least one task will be impaired. When the time delay between presentations of two stimuli is reduced, there is an increase in the processing period during which capacity is shared between tasks; this leads to a rise in the overall time processing of the DT. This theory also predicts that it is also possible to voluntarily allocate capacity to a specific task.

While some capacity theorists claim that a single, central mental resource can account for performance limitations, extensions of the general capacity sharing model (*multiple resource models* [64,102]) postulate that task processing may require multiple types of resources. Two tasks will interfere with each other if they require common limited resources. Otherwise, it should be possible to perform them concurrently without interference.

By way of an example, Künstler et al.'s recent results for a continuous motor tapping task and a simultaneous visual information uptake task performed by middle-aged to older adults supported the capacity sharing model [43]. Given that the researchers observed DTCs for visual processing speed and visual short-term memory storage capacity but not for perceptual threshold, they concluded that even the performance of this quite simple motor task required central attentional capacity that was also needed for visual information uptake.

(ii) **Bottleneck theories**: In the bottleneck model, a deterioration in the performance of one or both tasks results from serial processing when the two tasks need the same neural processor or networks, or when the required networks overlap. In other words, certain processors act only on one input/task at a time. This leads to a bottleneck when processing information related to the two tasks and, ultimately, to a delay in or the impairment of one of both tasks [72,95].

One can further differentiate between *structural* [72,85,101] and *strategic bottleneck theories* [55,56].

On one hand, the *general (or central) structural bottleneck model* holds that so-called "bottleneck processors" are responsible for response selection and decision-making, whereas stimulus identification and response execution can operate in parallel [52,101]. However, as with resource limitations, single or multiple bottlenecks (related to different types of mental operations or different stages of processing) can arise [72]. Indeed, an example of another structural bottleneck model is the *dual-bottleneck model for overlapping-task performance* [23]. This model postulates the existence of a central bottleneck at the response selection stage and a late bottleneck at the response execution stage.

On the other hand, the *adaptive executive control model* [55,56] (a strategic bottleneck theory) postulates that under the right set of conditions, two tasks should virtually be able to share time perfectly. However, one or more of these conditions are usually violated, leading to the establishment of either a strategic bottleneck in controlling the response order or a peripheral bottleneck when both tasks require the same input and output processors. In contrast to the bottleneck processors in the general structural bottleneck model, strategic bottleneck processors can be invoked at any point in the information-processing stream.

A dual task involving a visuomotor compensatory tracking task and a visual detection task in healthy young adults provided evidence of a response processing bottleneck and thus support for a bottleneck theory [30]. Indeed, increased tracking errors and decreased joystick speed were only observed under conditions with target stimuli.

(iii) The **cross-talk model** predicts a sort of facilitation when two tasks are from similar domains and use the same neural populations, since the tasks would not disturb each other [65]. Indeed, use of the same pathway might increase the efficiency of processing by using less attentional resource capacity. This would explain the motor facilitation sometimes observed in patients with Huntington disease, for whom carrying a tray with glasses improves gait speed but counting backwards worsens it [24]. Once again, this motor facilitation was observed in some patients but not others - reflecting heterogeneity in individual processing and concurrent task automatization.

In addition to the three most influential DT theories, an interesting **time-sharing hypothesis** has also been proposed by Nijboer et al. (2014) [67]. The researchers' objective was to explain the under-additive, additive and over-additive cortical activations that occur during DT and depend on the nature of the concurrently performed tasks. Firstly, the time-sharing hypothesis postulates that time has to be shared between the two tasks. Therefore, brain areas that underlie only one task are less activated during a dual-task situation than during a single-task condition because they are less frequently accessed. Secondly, in the case of additive activation, one task does not take away time from the other; the two tasks share time and access to resources perfectly. Nijboer et al. also observed that the greater the resources overlap between two tasks, the greater the degree of interference and the higher the cumulative level of brain activation in overlapping brain regions. Thirdly, the time-sharing hypothesis postulates that over-additive activation is caused by additional processing stages not found in either single task. In particular, the over-activity observed in visual areas during DT can be explained by the time taken away from a visual task involved in the DT condition, leading to a potentially greater error rate and thus a greater effort required to avoid these errors.

*Insert Figure 2 around here*

## Dual-task paradigms

After having highlighted the discordance concerning the mechanisms underlying dual-task interference, we shall review factors that influence DTEs in dual-task paradigms performed by specific populations. Our goal is to better understand the variability in DT patterns and thus in neuropsychological theories. To this end, we shall focus on DT paradigms performed by healthy young adults and involving gait, gait initiation, posture or turns as the motor task; cognitive-motor dual tasks with various motor tasks and the interplay between attention and motor control have been extensively studied in the literature.

## Motor tasks

### *Gait*

Under standardized conditions (i.e. when the person does not have to take account of stimuli such as obstacles), walking is mainly under the control of subcortical locomotor brain regions and is therefore highly automatic and rhythmic [69]. However, several neuroimaging studies (using functional near-infrared spectroscopy, functional magnetic resonance imaging, electroencephalography and positron emission tomography) have evidenced the involvement of a large number of brain regions in walking performance (for a review, see Hamacher et al. (2015) [36]). These regions have been classified into a direct locomotion pathway (i.e. the primary motor cortex, cerebellum, and spinal cord) and an indirect locomotion pathway (i.e. the prefrontal cortex, premotor areas, and basal ganglia) [27].

In particular, it has been found that dual-task walking is associated with changes in the activation of the indirect locomotor pathway and the frontoparietal network (i.e. the cingulate cortex, parietal areas, and the insula) [36]. As mentioned above, these brain regions form part of the frontoparietal cortical regions associated with attention, working memory and EF. Together with the fact that the neural correlates of walking dual tasks involve high-level cognitive areas, the occurrence of cognitive-motor interference during DT reflects that gait requires cognitive control in general and attention in particular. Over the last decade, a large number of studies have investigated the interplay between cognition and gait in dual-task paradigms [2].

In most dual-task studies, gait speed is the outcome of interest [75]. However, other kinematic variables (e.g. stride length) can be altered in PD [26] and other neurological diseases [29]. Interestingly, the spatiotemporal variability of gait is of relevance for discriminating between patients with MCI and healthy older adults and thus for predicting the fall risk in the older population [60,89].

### *Gait initiation*

As is the case for other voluntary movements, gait initiation is preceded by anticipatory postural adjustments (APAs). These adjustments are the main variables studied in paradigms involving gait initiation. They are thought to have two main roles: the correction of the a perturbation caused by the subsequent movement (this is not true for gait initiation) or the acceleration of movement by increasing imbalance [18]. Indeed, the nature of an APA's functional role depends on whether the voluntary movement modifies the base of support. When the base of support is displaced as during step initiation, APAs generate the initial propulsive forces required for forward body progression and play a role in the transfer of body weight during the stance-to-swing transition [18,58]. Anticipatory postural adjustments can be assessed by monitoring the stereotypical trajectory of the center of pressure (COP): a backward displacement toward the swing leg is followed by a lateral shift toward the stance leg. The start of the second phase of COP displacement is characterized by heel-off of the swing leg, while toe-off occurs at the end of this mediolateral COP displacement - just before the so- called "swing phase". The latter follows APAs, and is characterized by a forward COP displacement until foot contact of the swing leg occurs [25].

Under certain conditions (e.g. choice reaction time paradigms [97] involving not only sustained attention but also other attentional components like orientation [94]), APAs may be first executed on the wrong side – i.e. towards the stance leg – and are subsequently corrected at the cost of an increased step latency. This type of APA is referred to as an "APA error" [21].

Furthermore, it has to be noted that APAs also occur during and after the end of a voluntary motion [108]: they are called compensatory postural adjustments and occur at the end of the first step. Their role is to brake the vertical fall of the center of mass. A comprehensive review detailing these aspects can be found in [109].

Even though relatively few research groups are studying gait initiation under DT situations in order to investigate the interaction between cognition and motor control, this is a promising field of research. Indeed, stepping initiation demands more attention than steady-state walking [92]; according to Uemura et al. (2012), dual-task interference may be more apparent during stepping initiation [96]. Accordingly, analyzing the effects of dual tasks involving auditory [25,93] or visuospatial [94,97] concurrent attentional tasks has demonstrated that attention and its components can modify step preparation and execution. Gait initiation is a key paradigm because we all know how important it is to be able to take a quick step in order to avoid falling over - regardless of the nature of the fall [13]. In this context, delayed step execution time in a stepping choice reaction time task was viewed as a strong predictor of falls in older adults [49].

### *Posture*

Posture has been defined as the spatial organization of the body segments [14,103]. In order to maintain an upright stance, the central nervous system (CNS) integrates a variety of sensory cues from visual, somatosensory and vestibular channels [31,63]. Sensory information may concern the body's orientation but may also be related to force vectors that trigger muscle activity [39]. Subsequently, the CNS couples the sensory information to muscle activity. In fact, the CNS must continuously scan the environment and adjust the body's posture as a function of often frequently changing demands.

The main problem with postural studies is that there is no consensus on the parameters that are relevant for the study of postural control. Most of these parameters are not redundant; hence, the minimum set of parameters required for the estimation of overall postural control is still subject to debate. Nevertheless, COP velocity and COP variability (the standard deviation or root-mean-square of the position, etc.) are the most frequently measured parameters in the literature.

If we focus our attention on a specific type of dual-task paradigms involving posture, models of dual-task performance will include the main DT theories described above in addition to other particular models. Again, there is no consensus on a suitable cognitive model that explains postural control in dual-task situations (for a review, see Bonnet & Baudry (2016) [15]). Almost all of the proposed models (other than the synergistic model [16]) suggest that above a certain level of complexity, the two tasks being carried out compete for attentional resources. Accordingly, the capacity sharing model [104] has been developed. Furthermore, the nonlinear interaction model [44] (with a proposed U-shaped relationship between postural control and cognitive demand) tries to explain why body balance improves when performing a relatively easy concurrent cognitive task but diminishes when the concurrent task's cognitive demand increases. The ecological approach is yet another model of postural DT performance [83]; it holds that "postural control is constrained by the perception of the kinematic consequences of control actions". In other words, postural control may primarily enable and facilitate other activities. For example, marked sway induces saccade variability in a visual concurrent task. Thus, a stable posture would facilitate successful visual task performance [83]. Mitra et al. (2003) have suggested a hybrid DTC model that combines the concepts involved in the capacity sharing model with the ecological approach [57]. The problem with this hybrid model is that it mixes two antagonistic and indeed incompatible explanations of postural control under DT, namely (i) a deterioration in postural control (an increase in postural sway) from the capacity sharing model and (ii) an improvement in postural control (a decrease in postural sway) from the ecological approach.

More recently, Bonnet & Baudry (2016) published a higher-order cognitive model of postural control that (unlike all the above-mentioned models) does not seek to quantify sway in one task relative to another [16]. In fact, the model focuses on the presence or absence of synergy between the sensory system and the postural control system. When individuals are performing a dual task involving exploration of the environment with no specific goal, the synergistic model predicts the absence of a significant relationship between sensory and postural systems: the CNS easily controls the two systems individually. However, when individuals are carrying out a dual task involving a precise sensory (visual, sound or haptic) interaction with the environment, the CNS controls the sensory and postural systems synergistically. By way of an example, the synergistic model predicts that if a healthy, young individual intends to perform a precise saccade 10° to the left and if his/her body oscillates by 0.1° to the left at the same moment, the saccade required to reach the target without correction should be 9.9° (and not 10°). This new cognitive model has been tested in healthy young adults [16] and is now being studied in older adults and PD patients.

### *Turning*

In the field of dual-task gait, many researchers have investigated straight-ahead walking. However, transition movements during walking (such as turning) have not been addressed extensively, despite the frequency of these movements in everyday life. Turning is of special interest because this transient motor activity is closely linked to instability - even under single-task situations. This instability might result from the unique physiological and cognitive requirements of turns (relative to straight-ahead walking [38,70]), such as the cognitive processing of speed [70]. Indeed, it has been hypothesized [20] that turning is not an automatic process but requires cognitive processing (i.e. the integration of information from the visual, vestibular and somatosensory systems) throughout movement, so as to provide feedback and control the body correctly.

## Factors in dual-task paradigms that influence interference effects

The dual-task interference effects reported in the literature are not always consistent because of inter-study differences in the study populations (e.g. demographic aspects, a history of falls, balance- related confidence, level of physical activity, general health, symptoms of depression, health-related quality of life, and motor and cognitive abilities) [35,76], measurement parameters [10] and specific features of the dual-task paradigm. In the following section, we shall review how DTEs in healthy young adults are influenced by (i) the motor task conditions, (ii) the nature and complexity of the concurrent cognitive task, and (iii) the instructions given before and during the task.

### *The motor task conditions*

The conditions and nature of the motor task are known to influence interference effects in cognitive-motor DT - even in healthy young adults.

Interestingly, Wrightson & Smeeton (2017) suggested the presence of different top-down control strategies as a function of the walking task's modality and thus novelty (e.g. treadmill vs. over-ground walking) in healthy young adults [105]. Despite the absence of differences in perceived task difficulty and cognitive task performance between these dual-task walking paradigms, stride time variability was greater for dual-task over-ground walking (but not for treadmill walking) than in the single-task walking condition.

Furthermore, walking conditions appear to influence the DTCs, since they increase the complexity of the motor task [10,12,19,41]. Beurskens et al. have reported on a main effect of the walking condition (e.g. walking along a wide, narrow or obstructed pathway) on both motor DT cost and overall DT cost (i.e. an average measure of both motor and cognitive DT costs). This effect was consistently observed across dual-task walking conditions that involved different secondary cognitive tasks. Walking along a narrow pathway seemed to have the most negative impact on DT performance in healthy young participants [10].

The walking direction (forward, backward or sideways) also leads to differences in dual-task interference effects [1], with more pronounced motor DTCs for backwards walking than for forward gait and even higher DTCs for sideways walking vs. backwards walking in healthy older adults. The greater DTC for backwards walking vs. forward gait had previously been reported for healthy older adults by Hackney & Earhart [34]. These findings might be due to the novelty and complexity of such motor tasks.

Furthermore, Patel et al. (2014) suggested that walking speed has an impact on cognitive task performance during DT. With high-complexity cognitive tasks (such as the Stroop task), slow walking enables to divert greater attention to the cognitive task; in turn, this produces a lower cognitive cost of dual-task walking and a greater motor cost [73]. In the case of less complex cognitive tasks (such as visuomotor reaction time tasks), healthy young adults prioritized the walking task under a slow- speed dual-task condition, in order to maintain the intended, self-selected, slow speed during DT.

Postural dual tasks and the related DTCs also depend on the postural task's complexity. For instance, changes in the base of support and visual manipulation influence the DTE in healthy young adults - even though these interference effects varied from one study to another because of likely differences in other experimental parameters (such as the cognitive concurrent task or the instructions given) [46,80–82]. Even though changes in the conditions for gait initiation and turning have not yet been thoroughly assessed, a recent study of a complex gait initiation task with walkway obstruction in young individuals [37] reported that the APA phase (but not the reaction time phase or cognitive task performance) slowed as the complexity of the motor task increased.

### ***The type and complexity of the concurrent cognitive task***

***Gait***

In the context of walking dual tasks in healthy young individuals, Beurskens et al. (2012) have demonstrated that gait impairments depend on the type of concomitant task [11]. More particularly, the researchers found that a concurrent motor task (e.g. hand engagement) had a greater negative impact on walking than a complex cognitive secondary task involving EF (e.g. a go/no-go task) did. This finding can be discussed in the light of the above-mentioned multiple resource models or structural bottleneck theories of attention. Indeed, it has been suggested that a walking task and a concurrent motor task share more cognitive resources because they both require motor control. Consequently, the resulting dual-task interference is greater than that related to a cognitive concomitant task, and performance decrements in both motor tasks are more pronounced. However, these results contrast with Walshe et al.'s (2015) report of higher DTCs for a concurrent task involving EF (relative to a non-executive motor task) [100]. It is difficult to draw firm conclusions about the difference in impact between a motor and a cognitive concurrent task because (i) the tasks' level of complexity and novelty influences the DTCs and biases the comparison, and (ii) motor tasks always feature a cognitive component to some extent.

In the specific case of a cognitive concurrent task, Patel et al.'s (2014) study in healthy young adults found that the prioritization of cognitive task depends on the type of cognitive task [73]. While simultaneously walking and performing a Stroop task, the young adults prioritized the complex cognitive task over the motor task. However, they prioritized gait when carrying out a dual task with a visuomotor reaction time task as the concomitant cognitive task. The capacity sharing theory explains these observations by either (i) the supposedly less challenging nature of the visuomotor reaction time task (relative to the walking task) and individual's ability to voluntarily regulate the allocation of attentional capacity, or (ii) the use of greater processing resources (i.e. the extensive network of brain areas involved) in the Stroop task than in the other cognitive tasks studied. Furthermore, Al-Yahya et al.'s (2011) review suggested that a dual-task walking condition in which the cognitive task involves internal interfering factors (e.g. mental tracking tasks) would induce greater gait disturbances than when the cognitive task involves external interfering factors (e.g. a reaction time task) [2]. This would also suggest that higher-order shared networks induce greater interference than lower-order shared networks.

Moreover, Oh and La Pointe (2017) have recently evidenced the impact of cognitive load on gait parameters in a dual-task walking paradigm [71]. Indeed, as the complexity of the concurrent cognitive task rose, young healthy adults showed a lower Functional Ambulation Profile score, a lower velocity, a shorter stride length, and a greater double-support time. As a lower Functional Ambulation Profile score has been linked a risk of future injurious falls [66], a high cognitive load while walking might be associated with a greater risk of injurious falls.

***Posture***

Overall, the outcomes reported in the literature on dual-task postural control differ from one study to another, due to differences in the type of tasks, the sensory modality solicited by the concurrent task, the task's responsiveness, the instructions given, and the nature of the cognitive resources used [79].

With regard the concurrent task's sensory modality, Redfern et al.'s results suggested that postural control would give greater weight to the sensory channel that is significant for both posture and the concurrent task. In other words, a sensory channel required for balance would enhance information processing more than another sensory channel. Since vision is known to be more involved than audition in balance, sensory channels might be shared between the postural task and a concurrent visual task; hence, there would be less interference than with a concurrent auditory task [79]. Therefore, performing a concurrent task that presents sensory conflict with balance could have a negative impact on postural control during a dual task. This effect might be exacerbated in older adults with reduced sensory abilities, and might lead to poor balance and falls.

Furthermore, Lajoie and colleagues have suggested than the discrete vs. continuous nature of a concurrent cognitive task has an effect on postural control; in young adults, continuous cognitive tasks were associated with more efficient postural control than discrete tasks were [45]. These findings confirm the idea that continuous tasks facilitate automatic postural control by reducing conscious postural control.

Lastly, Boisgontier et al.'s (2013) literature review emphasized the importance of the choice of both the main postural task and the concurrent cognitive task [14]. Indeed, sensitivity to age-related impairments in DT increases with the complexity of the postural task (e.g. an unstable surface, or visual manipulation), and especially with the complexity of the concurrent task [14,79].

***Turning***

The nature and complexity of the concurrent task have not yet been thoroughly investigated in the context of dual tasks involving turning in healthy young adults. However, as has already been seen for gait and posture, dual-task processing appears to depend on the type and complexity of the secondary task. Porciuncila et al. (2016) studied interference effects in dual-task processing during specific phases of a dual-task timed up-and-go test in healthy younger and older adults [77]. The

DTCs were calculated from the duration and peak trunk velocity of each phase. The researchers found that the DTCs associated with a manual secondary task were situated between those associated with a cognitive secondary task and a cognitive-manual secondary task; cognitive-manual secondary tasks having showed the highest DT interference.

## *The task instructions*

### *Gait*

The instructions given before performing a walking dual task also influence gait performance, although the influence differs in healthy young adults vs. older adults. Yogev-Seligmann and colleagues tested the impact of instructions before a DT walking condition in which a verbal fluency task served as the concurrent cognitive task [111]. The researchers asked the participants to prioritize either gait, the cognitive task, or neither. Task prioritization tended to alter gait speed (the outcome) more in healthy young adults than in older adults. Hence, in young adults, the gait speed was significantly higher when gait was prioritized than in the absence of specific prioritization, and tended to diminish when the cognitive task was prioritized. The lesser influence of prioritization instructions on gait speed in older adults might be due to an age-related decline in the ability to flexibly allocate attention to one task or another. Secondly, gait variability was affected only in healthy older adults and, particularly, increased in the same way under all DT conditions compared to the single-task condition. There was therefore no effect of instructions on gait variability. Indeed, older adults seem to have more difficulties for maintaining a "posture first" strategy under DT conditions, whereas gait variability in healthy young people is regulated in a largely nonconscious/automatic way. Lastly, Yogev-Seligmann et al. (2010) found more changes in gait speed with respect to task prioritization in young women than in young men but were unable to find a clear explanation [111]. Kelly et al. (2010) observed similar DT performance in healthy older adults in response to instructions [42].

### *Gait initiation*

It is noteworthy that the effects of dual-task interference on gait initiation depend (at least in part) on the strategy used. For example, in the particular case of a choice step execution task (i.e. a dual task involving gait initiation and a flanker interference task), the participants can choose to prioritize speed (motor task prioritization) or accuracy (cognitive task prioritization) or to aim at a speed- accuracy trade-off [98]. Such a strategy can be imposed by giving specific instructions to the participants. In Uemura et al.'s (2013) study of the instructed prioritization of speed over accuracy in healthy young adults, the researchers observed a shorter RT, swing phase and total step execution time but a greater APA error rate under conflict resolution conditions, compared with the accuracy strategy [98]. However, the step error rate did not differ significantly as a function of the instructions.

Later, Sun and Shea (2016) demonstrated that as well as depending on instructions and environmental factors, task prioritization is also related to the complexity of the step initiation task and concurrent cognitive task, and the APA error rate [91].

***Posture***

With regard to the effects of instructed prioritization of one task over another, Yu & Huang (2017) have recently reported that (in contrast to a posture-focused strategy) a supraposture-focused strategy (i.e. a focus on the concurrent task) was associated with better postural and concomitant task performances in both healthy young adults and older adults performing a posture-motor dual task [112]. The prioritization of the concurrent task could thus be used as a tool for fall prevention in DT situations. Yu & Huang's results [112] are consistent with the constrained-action hypothesis proposed by Wulf & Prinz (2001) [106]. It should be noted that a similar effect was not observed when the participant focused on a cognitive suprapostural task [112].

***Turning***

Concerning dual tasks involving turns, Smith et al. (2017) [88] observed a significantly more consistent walking turn performance (90° ipsilateral walking turns at a controlled speed of 1.5 m/s) under a dual-task condition involving divided attention (a verbal two-back working memory task) in young healthy individuals instructed to prioritize the cognitive task over the walking turn. In particularly, step length variability decreased significantly with divided attention. These results were consistent with Wulf's (2013) [107] statement that motor performance and learning are enhanced when attention is redirected from an internal focus (i.e. a focus on body movements) to an external focus (i.e. a focus on the movement effect) - perhaps because of greater automaticity of the walking turn performance under this condition. With regard to prioritizing the cognitive task, Smith et al. (2017) also found no change in two-back task accuracy but did observe significantly lower intersegmental coordination variability due to divided attention [88]. Although an optimal level of stride-to-stride coordination variability is necessary to ensure an adaptable use of degrees of freedom and therefore correct turning during gait, the lower variability in intersegmental coordination appears to be still enough to consistently improve walking turn performance under DT conditions. Smith et al. observed a less pronounced effect of divided attention on joint excursion.

## Conclusion

Experiments in dual task situations have shown that not only attention but also other cognitive processes have important roles in posture and locomotion in healthy older adults and especially in patients with neurological disorders. Dual-task paradigms also allow one to measure disability and to monitor disease progression and the effectiveness of interventions. Ultimately, behavioral data and neural correlates related to DT might prompt the identification of key targets for diagnosis and therapy.

Nevertheless, a number of shortcomings persist in the literature with regard to movements of the lower limbs performed under dual-task conditions. Consequently, these shortcomings prevent us from drawing firm conclusions about the specific associations between EF and gait.

Firstly, too many studies still omit to report important details of the DT procedure - details that might enable a clearer analysis of the study outcomes. For example, several studies have not reported dual-task costs of the concurrent task. Nevertheless, cognitive DTCs are essential for understanding the prioritization strategy chosen by the participants and for discriminating between populations. Moreover, all the variables likely to influence dual-task effects and reported here should always be reported, in order to achieve replicable results.

Along with missing data, there is also a lack of standardization among dual-task paradigms. Inter- study differences variously concern the walking modality (treadmill vs. over-ground), walking conditions (wide, narrow, or obstructed pathway), walking direction and speed, task prioritization instructions, the nature and level of difficulty of the concurrent task, and consistency of the attentional load during DT performance (e.g. discrete vs. continuous cognitive tasks). However, we are now aware of the influence of all these variables on DTEs. Furthermore, this influence depends on the nature of the motor task. The choice of different measurement parameters can also emphasize various DTCs. As we gain more knowledge about gait during DT, researchers should start to normalize their methodology and thus be better able to compare their findings correctly.

Other limitations on inter-study comparisons include variability in the characteristics of individuals - even for those who supposedly belong to the same group. Indeed, too few studies have considered the contribution of individual characteristics - such as physical and cognitive impairments, age, concomitant medications, latent variables (e.g. fatigue, emotional state, motivation, pain or anxiety), and the perceived complexity of both walking and concurrent cognitive tasks - to DTEs during gait. By way of an example, trained athletes are subject to lower DTCs than healthy but sedentary adults [32].

Moreover, many studies performed in the laboratory lack ecological validity. In this respect, the use of mobile brain-body imaging (involving a mobile EEG system and inertial measurement units) appears to be very promising. Pressure-measuring insoles are also likely to have a promising future in home-based measurement.

Lastly, little research has focused on DTs involving gait initiation or turning as the main motor task. However, these motor tasks appear to be able to detect DT interference with high sensitivity. Therefore, future work should seek to better understand step initiation and turning DTEs, and to standardize dual-task methodologies. This standardization might then allow researchers to confirm literature data on a larger scale and thus to identify diagnostic and therapeutic targets with more confidence. For example, an agreement on a standardized DT paradigm for detecting older adults at risk of falls would help to solve this major public health issue. At present, a few therapeutic approaches seek to affect gait indirectly via cognition. Cognitive training and cognitive enhancers (e.g. methylphenidate, cholinesterase inhibitors, and memantine) are encouraging avenues of investigation but have yet to be assessed in large clinical trials in this field.

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**Table 1 A classification of cognitive tasks, adapted from Al Yahya et al. (2011) [2].**

| Category | Definition | Cognitive processes involved | Examples of cognitive tasks |
|---|---|---|---|
| *Reaction time tasks* | Tasks assessing the elapsed time between a single sensory stimulus and a behavioral response | Processing speed and vigilance/sustained attention | - Push-button simple reaction time |
| *Discrimination and decision-making tasks* | Tasks that require selection of a specific stimulus (or feature) and production of a specific response to the stimulus | Selective attention and response inhibition | - The Stroop paradigm<br>- Visuospatial decision tasks (e.g. the auditory clock task: listening to the time of day and determining whether the clock's hands are on the same side or different sides of the clock face)<br>- Color/number classification task: listening to auditory stimuli consisting of colors/numbers and answering "yes" or "no", depending on the stimulus<br>- Auditory choice reaction time task: reporting whether the pitch of an auditory tone is high or low |
| *Mental tracking/working memory tasks* | Tasks that require information to be kept in mind while possibly manipulating the | Sustained attention, information | - Serial subtractions;<br>→*PL+CE*<br>- Counting backwards; |

| | | | |
|---|---|---|---|
| | information in a mental process | processing speed and working memory (with its four components, according to Baddeley's model [3,7]: the central executive (*CE*), the phonological loop (*PL*), the visuospatial sketchpad (*VSS*) and the episodic buffer (*EB*) | →*PL+CE*<br>- Backward spelling;<br>→*PL + CE*<br>- Arithmetic tasks;<br>→*PL/VSS + CE*<br>- Reciting the months of the year in reverse order;<br>→*PL+CE*<br>- Repeating a series of digits forwards;<br>→*PL*<br>- Counting how many times predefined words appeared in a text read aloud;<br>→*EB + CE*<br>- Remembering a short item-shopping list;<br>→*PL/VSS*<br>- Listening to a text and answering questions about it.<br>→*EB + CE* |
| *Verbal fluency tasks* | Tasks that require the production of words spontaneously or under pre-specified search conditions | Executive function and semantic memory | - Reciting words (e.g. names of animals or professions) with or without specific letters<br>- Simple counting<br>- Spontaneous speech task |

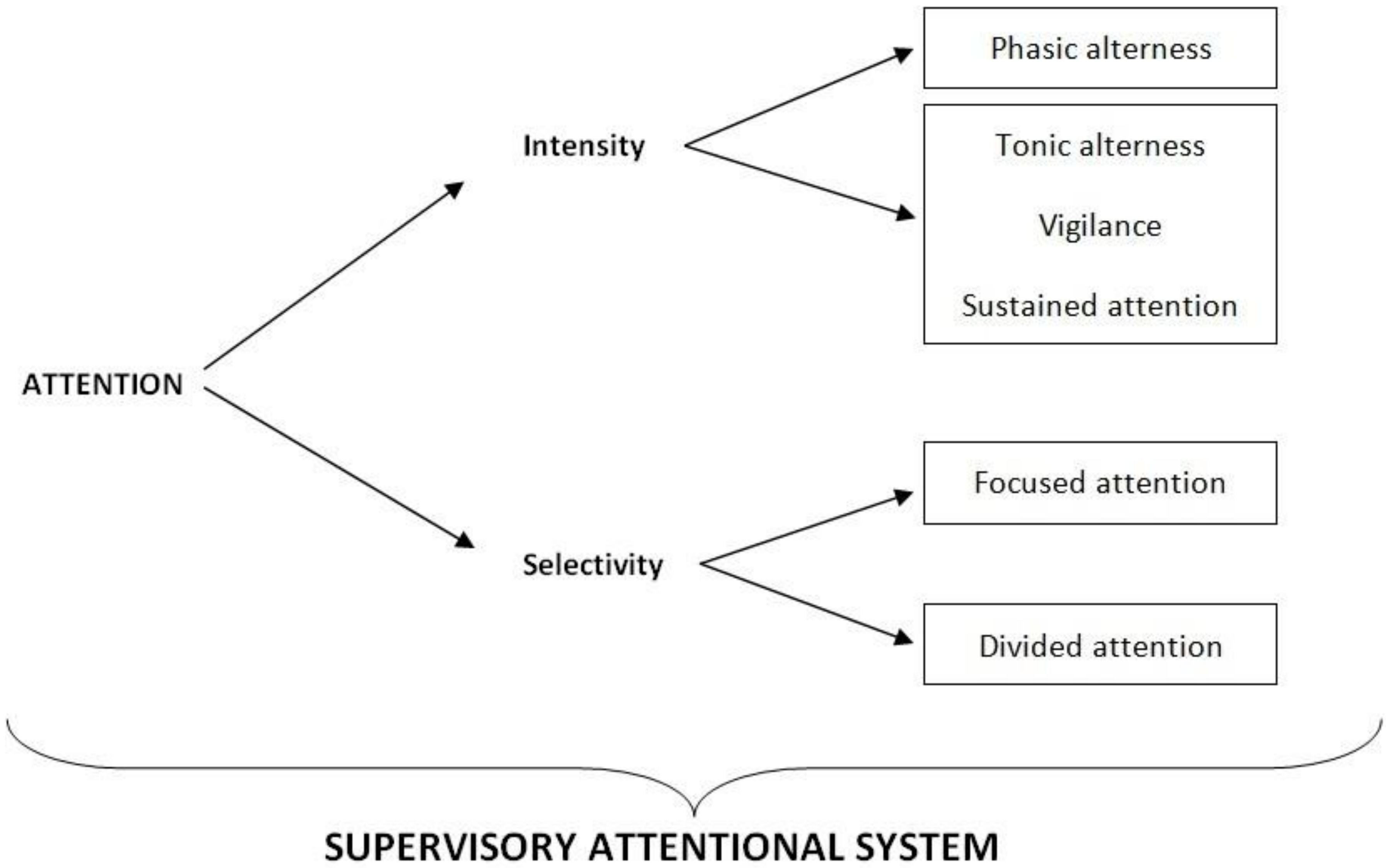
**Table 2 The nine potential patterns of cognitive-motor interference proposed by Plummer et al (2013) [76].**

| | | Cognitive performance | | |
|---|---|---|---|---|
| | | **No change** | **Improved** | **Worsened** |
| **Motor performance** | **No change** | No dual-task interference | Cognitive facilitation | Motor-related cognitive interference |
| | **Improved** | Motor facilitation | Mutual facilitation | Motor-priority trade-off |
| | **Worsened** | Cognitive-related motor interference | Cognitive priority trade-off | Mutual interference |

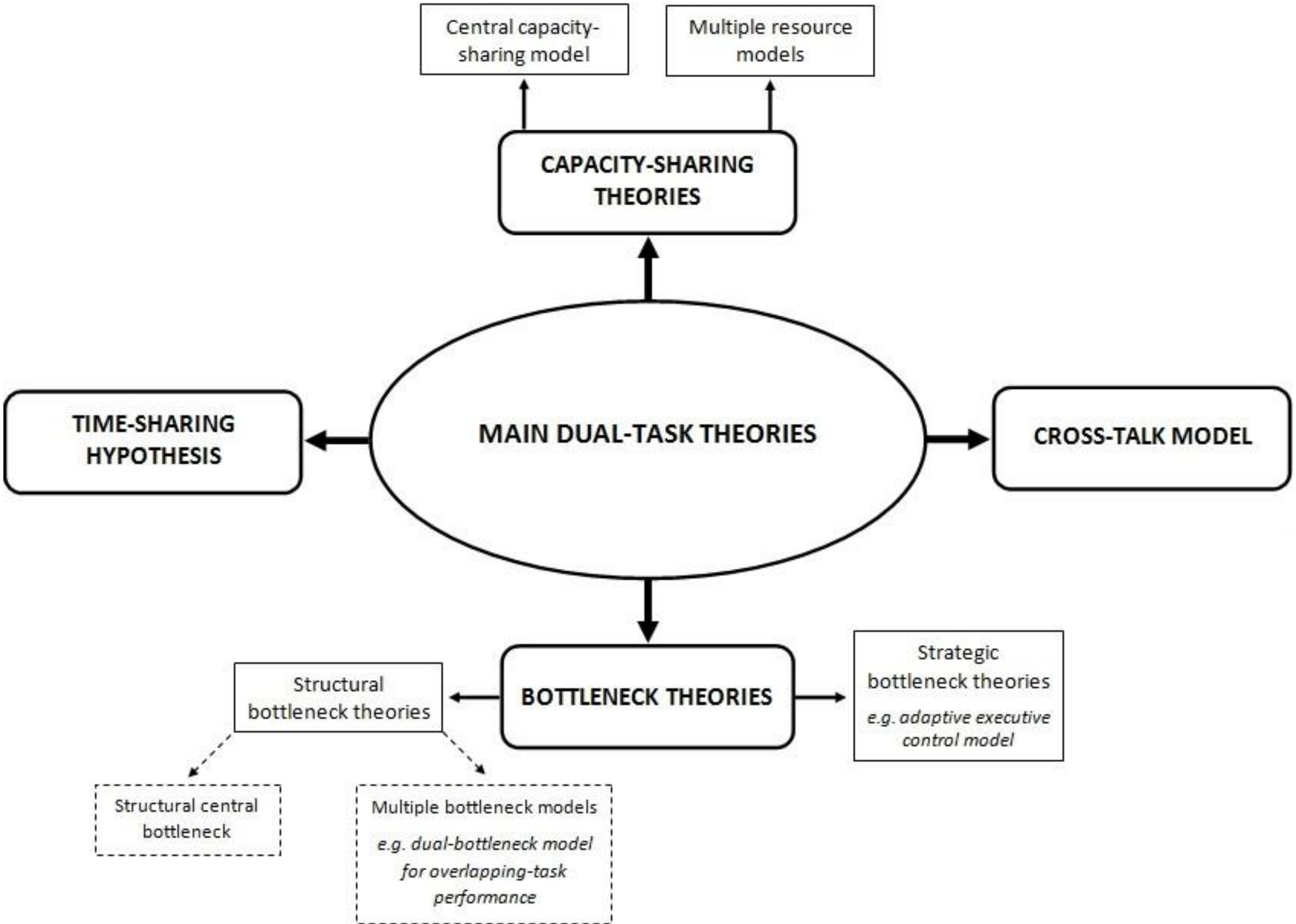
**Figure legends:**

**Figure 1 van Zomeren & Brouwer's model of attention (1994) [113].**

**Figure 2 The main dual-task theories.**



Phasic alterness
Intensity
Tonic alterness
Vigilance
Sustained attention
ATTENTION
Focused attention
Selectivity
Divided attention
SUPERVISORY ATTENTIONAL SYSTEM


Central capacity-sharing model
Multiple resource models
CAPACITY-SHARING THEORIES
TIME-SHARING HYPOTHESIS
MAIN DUAL-TASK THEORIES
CROSS-TALK MODEL
Structural bottleneck theories
BOTTLENECK THEORIES
Strategic bottleneck theories
e.g. adaptive executive control model
Structural central bottleneck
Multiple bottleneck models
e.g. dual-bottleneck model for overlapping-task performance