Using dual-task effect for cognitive-motor change profiling – the Dual-Task Progress model and its dedicated software

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ABSTRACT

Dual task situations are very common in daily life. The cost of dual task conditions has been widely used by researchers and clinicians to categorize individuals, as indicators of decline in functional capacities of older persons or people with cognitive or motor disabilities. Moreover, the comparison between performances in single and dual task situations enables the calculation of the dual task effect, which can be either beneficial or detrimental for the component cognitive or motor tasks. Based on results of a previous interventional study, we defined a dual task model analysis from the evolution of the dual task effect after 12 weeks of exergaming in older adults. This approach led us to the proposal of a representation of the dual task progress (DTP). This theorical model is sensitive to the reliability of dual task outcome measures and needs to be validated in the future. In this viewpoint article, we begin by defining key concepts based on existing literature. We then analyse additional data from a previous study, leading to the step-by-step development of a new model. Finally, we provide the DualTaskProgress free and open-source software that enables calculation and graphical representation of the DTP.

KEYWORDS: Dual-task; older adults; cognitive-motor interference; training; theorical model; python

Dual task (DT): historical background, paradigm, and definition

We will systematically discuss "dual task" as cognitive-motor dual task, which involve performing both a cognitive task and a motor task simultaneously. Sequential cognitive-motor dual task also exist according to some authors [1, 2, 3, 4], as well as motor-motor dual task, which we will not address. To simplify reading, the acronym "DT" will consistently refer to "simultaneous cognitive-motor dual task".

Introduced by Abernethy et al. in 1988 [5] and subsequently studied by others [6], the dual task (DT) paradigm was initially used to study changes in walking patterns [7]. Gait and postural control require minimal attentional resources in healthy population, allowing another concurrent task to be added, typically a cognitive task. However, in certain clinical conditions, performing this second task can be challenging or even impossible, potentially leading to deterioration in the performance of either (or both) the cognitive or motor task [8]. The concept of the DT cost was then introduced, initially representing the deterioration of cognitive or motor performance when performed in DT compared to single-task (ST) conditions [9]. The DT cost has been widely used by researchers to categorize individuals, and has been perceived as indicative of functional decline (e.g. reflecting the risk of falls) [10]. While conceived as a measure of deterioration in task performance, DT cost may also signify improvement in performance, such as those observed following a targeted intervention [11]. The calculation of the DT cost requires the evaluation of each task in DT and ST condition as follows [12]:

$$\text{DT cost} = \frac{(DT - ST)}{ST} \times 100$$

This can be illustrated with the motor performance of an adult taking a Timed-up-and-go test under ST (6s) and DT condition (9s) (*i.e.*, with concurrent arithmetic task). The motor DT cost would then be equal to $\frac{(9-6)}{6} \times 100 = 33\%$. Considering the direction of the TUG test

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score, this motor DT cost value means that carrying out the TUG test with a concurrent arithmetic task results in a reduction of the motor performance of 33% compared to TUG test alone for this person. In other words, it takes 50% more time to realize the TUG in DT compared to ST.

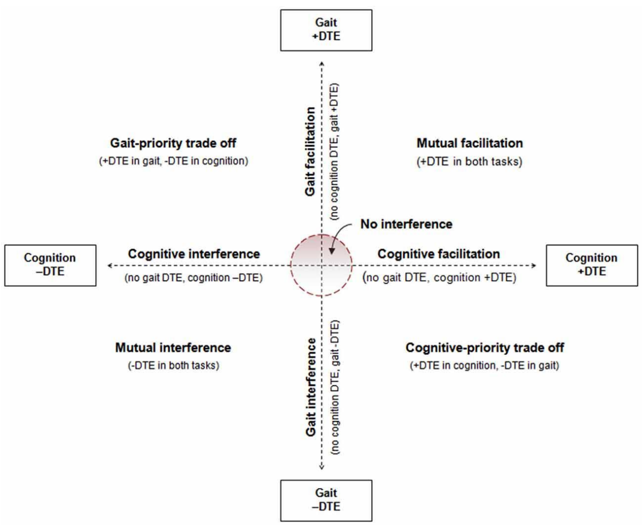


Figure 1 **Patterns of cognitive-motor interference - DT effect model (DTE) proposed in Plummer et al. 2013 [13].**

Positive values for DTE indicate that performance improved in dual task condition relative to single-task performance. Negative values for DTE indicate that performance deteriorated in dual task condition relative to single-task performance. The different combinations illustrate interference, facilitation and tradeoff scenarios between cognition and gait.

The cognitive-motor interference (CMI) concept and associated models

The concept of cognitive-motor interference (CMI) is an explanatory model of DT cost that highlights deterioration, or mutual facilitation strategies. Various models of CMI have been proposed since its initial description in 1994 by Pashler et al. [14], recently reorganized [9]. These models include: 1) the cross-domain competition model [15, 16], which is a volume-dependent model based on an individual's attentional resource capital; 2) the bottleneck theory [17], a time-dependent model based on task coordination and attention-sharing capacity; 3) the task prioritization model [18], relying on individual-specific adaptive strategies; 4) the time-sharing hypothesis [19], which suggests that the deteriorated performance in DT is due to additional processing steps not present in any of the separate ST, and; 5) the cross-talk model [20], a model of reciprocal facilitation in the case of similar neural networks. These models are widely recognized, developed, and commonly used. For brevity, these models are only mentioned in the present paper; the included references may be consulted for more detailed descriptions.

In these different theoretical models, and especially in the crosstalk model, the consequence of the DT is not necessarily associated with performance deficits [20]. Plummer et al. 2013 synthesized [21] and illustrated [13] these different scenarios with patients after a stroke. According to these authors, the DT situation can lead to either deterioration or improvement of cognitive and/or motor performance, schematized by 8 different scenarios (Figure 1). The additional task may induce mutual facilitation, but this would be less frequent than deterioration. Using the exact same calculation equation, the DT cost is now referred as the dual task effect (DTE) [9], which includes the potentially beneficial consequence not expressed by the term "cost", as illustrated in the "tradeoff" and "mutual facilitation" quadrants. Tradeoff refers to a compromise where one cognitive or motor performance is sacrificed for the other. Mutual facilitation, on the other hand, denotes a scenario where both performances are enhanced, in opposition to mutual interference. It is worth noting that the "no interference" central area presented in the model is not defined as a percentage of the cognitive or motor DTE.

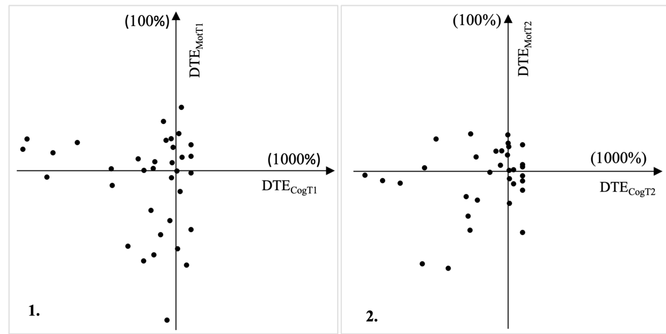


Figure 2 **Cognitive and motor DTE at T1 (1) and T2 (2) (N = 34).** DTE_{Cog}: cognitive dual task effect. DTE_{Mot}: motor dual task effect.

This figure illustrates the cognitive and motor dual task effect at T1 and T2 for our 34 participants. It demonstrates the influence on performance when performing identical cognitive and motor tasks under single and dual task conditions. Each point displays a participant, positioned at the intersection of the disparity between their single and dual task cognitive performance (DTE_{Cog}), and between their single and dual task motor performance (DTE_{Mot}). To enhance clarity, we have extended the x ticks to 1000%. Consequently, a decrease in motor performance of 10% and cognitive performance of 20% when transitioning to dual task conditions will be depicted as 10% and 200%, respectively, causing the data points to move further apart.

CMI patterns are neither fixed nor constant and depend on various factors, including individual characteristics (especially cognitive and motor abilities) [21], the nature [8, 22], difficulty, and novelty [23] of primary and secondary tasks [24] or the "first strategy" adopted by the person (cognitive or motor). The "first strategy" refers to the preferential domain prioritized by the person. For instance, a motor first strategy involves prioritizing motor tasks over others (minimizing potential distractions), often to preserve physical integrity and ensure safety (e.g., reducing the risk of falls). This is commonly observed in situations like "stop talking when walking". The way in which the test is administered, and more particularly the instructions regarding the task to prioritize, also influence the strategy adopted by the patient [8, 21]. Overall, the DTE is mostly observed as a CMI in neurological diseases [25] and aged populations [26], who present with deteriorated performance in DT conditions. In addition, the DTE is frequently calculated only for one of the two components (*i.e.*, cognitive or motor) [27] while a lot of tasks include both motor and cognitive resources in the daily life. Therefore, it is important to test the relevance of this theoretical DTE model to highlight the different strategies for DT. This is particularly true given the significant heterogeneity of the literature. Over the past decade, numerous studies have used DT as the primary intervention and/or outcome, whether in posture or walking, across various training programs for healthy or pathological older adults. In the past 10 years, 16 studies can be cited (among many others) exposing the extent to which methods have been varied, with heterogeneous and sometimes controversial results [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. This can be explained by the numerous parameters influencing the DTE mentioned earlier. Thus, the precise definition of individuals' profiles or their progression becomes challenging within the complexity of dual tasking. Taken together, this complexity complicates the personalization of rehabilitation interventions, as goals and methods depend on individuals' characteristics.

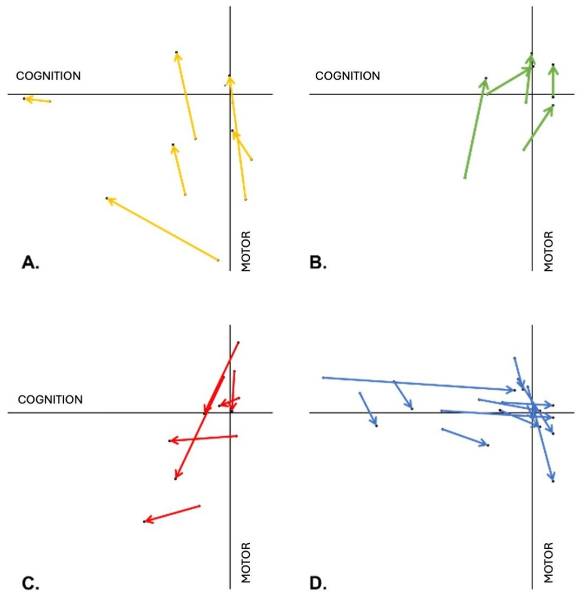


Figure 3 **DTE progress after 3 months of DT training (N = 34).** Four different scenarios: decreased DTE for motor, increased DTE for cognitive abilities (A); decreased DTE for both cognitive and motor abilities (B); increased DTE for both cognitive and motor abilities (C); increased DTE for motor, decreased DTE for cognitive abilities (D).

This figure illustrates the progression of each 34 participants from T1 to T2 regarding cognitive and motor dual task effects (DTE_{Cog} and DTE_{Mot}), called dual task progress (DTP). In other words, it represents the vector $\overrightarrow{DTP}$ going from DTE_{T1} ($DTE_{Cog\ T1}$: $DTE_{Mot\ T1}$) to DTE_{T2} ($DTE_{Cog\ T2}$: $DTE_{Mot\ T2}$). The number of participants per panel was A = 6, B = 5, C = 6, D = 17. 5 vectors are overlapping in panel D and cannot be shown properly all at once.

Findings from previous experimental research

Amongst the previous studies mentioned, an intervention was recently conducted [42] in which DT training was provided through an exergame consisting of 30 sessions lasting 30 minutes each, spread over 12 weeks, to 39 participants with an average 84.6 $\pm$ 8.5 years old age. The participants had no established diagnosed motor or cognitive impairments. Among other outcome measures, their mental inhibition performance was assessed using the number of errors in the Stroop test [44], and their postural control assessed using the speed of oscillation of their center of pressure (CoP speed) in standing balance [33]. The Plummer model was developed for postural control, and the advantage of this task compared to walking is that it provides a highly standardized setting that is easy to reproduce in clinical practice. These two tests were conducted in both ST and DT conditions (see the study protocol for more details [45]). Among other observations, after three months of exergaming, cognitive improvements were observed, with a 37% cognitive performance increase and no significant difference in motor performance in DT in 34 participants (see the study for more details [42]). This overall trend of cognitive improvement and motor maintenance appears to reflect a "cognition-first" strategy, to be confirmed or refuted by studying the DTE. The DTE on cognitive (DTE_{Cog}) and motor (DTE_{Mot}) performances were calculated before (T1) and after training (T2) for each participant. This computation entailed determining the number of errors made in the Stroop test and the difference in the CoP speed depending on whether the tests were conducted in ST or DT. The graphical representation of these performance variations is possible for each subject using the 8 scenarios from the Plummer model [13], providing information about the DTE profile for individuals at T1 (Figure 2.1) and T2 (Figure 2.2): mutual interference, motor or cognitive compromises, or mutual facilitation.
According to this representation, it seems that there is a recentering of the points towards the central non-interference area. A more precise analysis of this phenomenon requires a study of the movement of each point, *i.e.*, an analysis of the displacement between "baseline point" (T1) and "post-training point" (T2) to observe the impact of the training on DTE. This is represented in Figure 3; the axes are truncated for clarity, but the units, axis proportions, and points represented are strictly the same as in Figure 2. Four types of DTE modifications can be distinguished from these graphical representations. In one case, participants had a decrease in DTE for both cognitive and motor abilities, translating to the reduced deterioration (*i.e.* improvement) of cognitive and motor performance in DT comparted to ST (Figure 3.B). Conversely, some participants exhibited an increase in DTE for both cognitive and motor abilities (Figure 3.C). Finally, some had a decrease in DTE for their cognitive abilities while simultaneously increasing DTE for their motor abilities (Figure 3.D), or vice versa (Figure 3.A).
All behaviors can be observed, represented by vectors with varying magnitudes and directions. Some participants even change their DTE quadrant, transitioning from interference to mutual facilitation, for example. Again, the general observation seems to be a trend toward a return to the center - which cannot be represented for reasons of legibility – with a high inter participants variability.

Proposal for representing the dual task effect progress over time (DTP)

The variable response to DT training in terms of differences in cognitive and motor performance in ST and DT leads us to propose an illustration of the significant variability of DTE progress over time (DTP) (Figure 4). Inspired by the 8 scenarios in the Plummer model [13], this model offers a dynamic representation of behavior performance.
This proposal allows us to consider all scenarios: whether the progress is an increase or decrease in the difference between performance in ST and DT situations in both cognitive and motor performances. On the other hand, does the DTE increase or decrease in the participant over time in the cognitive and motor domains? It is important to note that the model is standardized and centered in this illustration, but movements can occur from any starting point to any endpoint on the diagram. What matters here are the magnitude and direction of the vector, characterizing the progress of the DTE (*i.e.*, DTP). This can be coupled with the individual's starting and ending quadrants, characterizing their DTE as proposed by Plummer et al. All scenarios of initial profile, progress, and final profile are possible. We present all the assessment, calculation and representation methods used to derive the DTP based on cognitive and motor assessments in Table 1. We also provide the DualTaskProgress free and open-source software that enables calculation and graphical representation of the DTE and DTP (https://dualtaskcalculator.streamlit.app/) (Figure 5). It is worth noting that even if the model was constructed using the combination of Stroop test as cognitive task, and static postural control as motor task, it is applicable in any scenario of combination (evaluation, test orientation, etc.).

Table 1 Assessments and calculations for dual task effect (DTE) and dual task progress (DTP)

	T1	T2
Evaluation		
Single task cognitive	$Cog_{ST\ T1}$	$Cog_{ST\ T2}$
Single task motor	$Mot_{ST\ T1}$	$Mot_{ST\ T2}$
Dual task cognitive	$Cog_{DT\ T1}$	$Cog_{DT\ T2}$
Dual task motor	$Mot_{DT\ T1}$	$Mot_{DT\ T2}$
Calculation		
Cognitive dual task effect	$DTE_{Cog\ T1} = \frac{(Cog_{DT\ T1} - Cog_{ST\ T1})}{Cog_{ST\ T1}} \times 100$	$DTE_{Cog\ T2} = \frac{(Cog_{DT\ T2} - Cog_{ST\ T2})}{Cog_{ST\ T2}} \times 100$
Motor dual task effect	$DTE_{Mot\ T1} = \frac{(Mot_{DT\ T1} - Mot_{ST\ T1})}{Mot_{ST\ T1}} \times 100$	$DTE_{Mot\ T2} = \frac{(Mot_{DT\ T2} - Mot_{ST\ T2})}{Mot_{ST\ T2}} \times 100$
Cognitive dual task progress	$DTP_{Cog} = DTE_{Cog\ T2} - DTE_{Cog\ T1}$	
Motor dual task progress	$DTP_{Mot} = DTE_{Mot\ T2} - DTE_{Mot\ T1}$	
Graphic representation		
Dual task progress	$\overrightarrow{DTP} = \overrightarrow{(DTP_{Cog};\ DTP_{Mot})} = \left(DTE_{Cog\ T1}\ DTE_{Cog\ T2};\ DTE_{Mot\ T1}\ DTE_{Mot\ T2}\right)$	

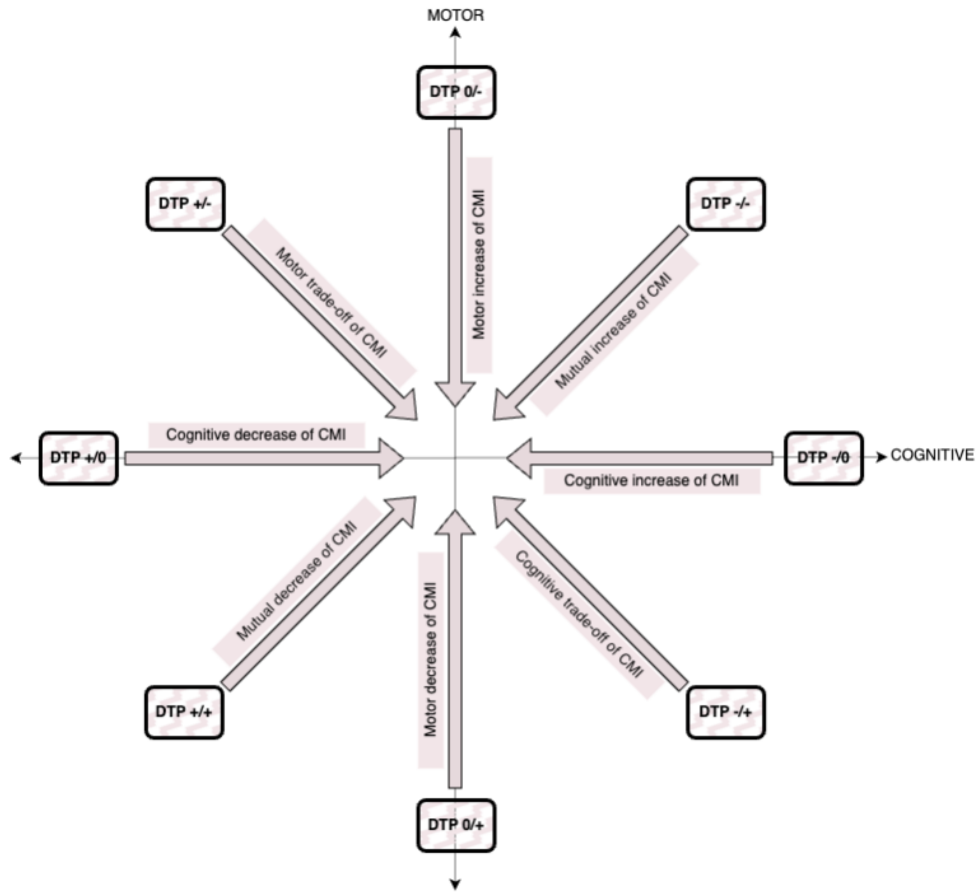


Figure 4 Representation model of the DTE progress (DTP cognitive / motor). DTP: dual task progress; CMI: cognitive-motor interference. As for the Plummer et al. 2013 model [13], 8 different scenarios exist.

This figure illustrates all scenarios possible regarding the dual task progress of individuals, written as DTP (cognitive / motor). As an example, let's consider the performance of one person taking a Stroop test (percentage of correct answers) and a static postural control test (CoP displacement), both realized independently and together (single-task and dual task conditions), before (T1) and after (T2) dual task training. The values obtained are:

	T1	*T2*
Stroop ST	*0.9*	*1*
CoP ST	*11*	*11*
Stroop DT	*0.7*	*0.9*
CoP DT	*13*	*12*

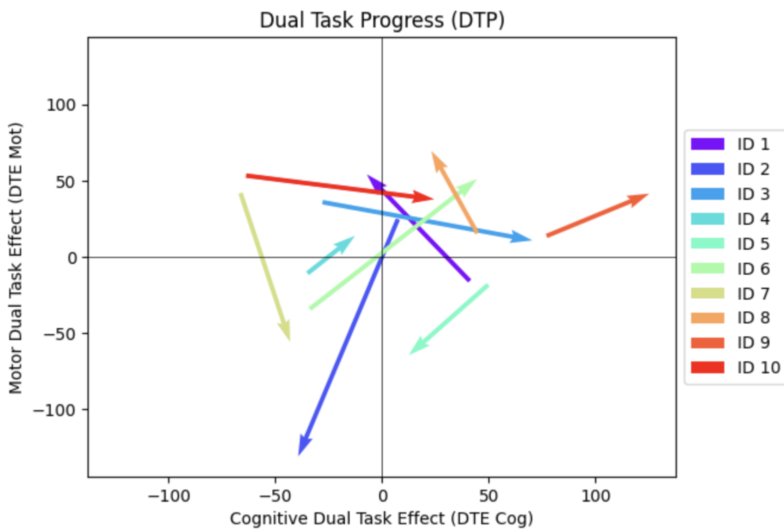
In this example, the training is efficient on every parameter in this person: the percentage of correct answers during Stroop is increased both in single and dual task conditions, and the CoP displacement is decreased in single task conditions. We can then calculate the dual task effect at T1 and T2:

	T1	*T2*
Cognitive DTE	*−22%*	*−10%*
Motor DTE	*−18%*	*−9%*

In this example, the person is impacted on both cognitive and motor performances in dual task compared to single-task condition, with a decrease in the percentage of correct answers during Stroop test, and an increase of the CoP displacement during postural control. Now we can estimate the dual task progress:

Cognitive DTP	*55%*
Motor DTP	*50%*

The dual task effect seems to decrease for both cognitive and motor performance. In other words, the person seems less impacted when dual tasking after training. Altogether, we can describe this person as in a mutual interference scenario before and after training, and with a mutual decrease of CMI, written DTP $+/+$. In a graphical illustration, this person would appear as a vector starting and ending in the bottom-left quadrant, with an up-right direction.

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Participant 1    : went from Cognitive priority tradeoff    at T1, to Motor priority trade off       at T2 with a DTP −/+ : cognitive trade−off of CMI
Participant 2    : went from Mutual facilitation            at T1, to Mutual interference            at T2 with a DTP −/− : mutual increase of CMI
Participant 3    : went from Motor priority trade off       at T1, to Mutual facilitation            at T2 with a DTP +/− : motor trade−off of CMI
Participant 4    : went from Mutual interference            at T1, to Motor priority trade off       at T2 with a DTP +/+ : mutual decrease of CMI
Participant 5    : went from Cognitive priority tradeoff    at T1, to Cognitive priority tradeoff    at T2 with a DTP −/− : mutual increase of CMI
Participant 6    : went from Mutual interference            at T1, to Mutual facilitation            at T2 with a DTP +/+ : mutual decrease of CMI
Participant 7    : went from Motor priority trade off       at T1, to Mutual interference            at T2 with a DTP +/− : motor trade−off of CMI
Participant 8    : went from Mutual facilitation            at T1, to Mutual facilitation            at T2 with a DTP −/+ : cognitive trade−off of CMI
Participant 9    : went from Mutual facilitation            at T1, to Mutual facilitation            at T2 with a DTP +/+ : mutual decrease of CMI
Participant 10   : went from Motor priority trade off       at T1, to Mutual facilitation            at T2 with a DTP +/− : motor trade−off of CMI
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Figure 5 Automatic representation of DTP, as well as initial and final DTE. DTE: dual task effect. DTP: dual task progress.

This is the results automatically computed by the free and open software dual taskProgress available here: https://dualtaskcalculator.streamlit.app/ (the data is fictitious and serves as an example only).

Discussion

In this study, the Plummer et al. 2013 analysis model of the DT [13] was confronted with the results obtained from a previous experimental study to assess the effect of 12 weeks of exergaming on the cognitive and motor function of older adults [42]. The main result of the initial study was an improvement in cognitive function, in ST and DT. The progress of the DTE (*i.e.*, DTP) was then calculated, and an overall movement of individuals towards the non-interference area was observed, with all different vectors. Based on these different scenarios, an improved model for discerning patient's strategies during the DT has been proposed: the DTP (Figure 4).

The primary advantage of this model is its ability to profile the effects of DT training according to individual strategies. The reasoning is similar to that of the force-velocity profile for muscular power training [46]: what type of training targets cognitive or motor aspects more? What are the responses of participants based on their characteristics? Initially, studying intervention programs according to the observed trends would allow for their characterization. In our study [42], the observed benefits appear to be primarily cognitive with an improvement in cognitive functions in the ST and in the cognitive performance in the DT. This training can then be considered relevant or not, depending on whether one targets cognitive or motor functions in DT within a comparable sample.

Secondly, the initial profile of participants based on the modified Plummer model [13] can be characterized: are they in a situation of interference, facilitation, or trade-off, in terms of cognition or motor performances? Coupled with rehabilitation goals, this should help determine the priority axes for each individual, such as giving cognitive prioritization through instructions during DT training for patients with motor facilitation trade-offs. Almost every action in daily life involves DT; therefore, it is of crucial importance to enable individuals to carry out their activities autonomously. Finally, studying the response of participants to interventions based on their characteristics may potentially allow the identification of response patterns and even threshold values for effects. Finally, to make the use of this DTP with initial and final DTE profiling more accessible, we have provided the dual taskProgress free and open-source software (https://dualtaskcalculator.streamlit.app/) (Figure 5).

Nevertheless, the notion of threshold value is crucial. Firstly, it is essential to determine the level of variation in DTP corresponding to a progression to know whether it is useful to train an individual in DT. Secondly, the notion of CMI remains vague: what percentage of difference between performance in ST and in DT corresponds to an interference situation? In other words, what does the central non-interference zone correspond to? It is likely that the answer to this question depends on the clinical significance of the combined cognitive and motor tests, but also on both the activity and the person concerned. This unknown minimal clinically important difference [47] values for DT effect have been raised since 2015 [48], and to the best of our knowledge, they have not been resolved since. All this can profoundly modify DT evaluation and intervention strategies in the future. We can imagine that the answer to these questions of threshold value and clinical significance could, in the future, be indicated by the characteristics of the DTP vector.

It is important to highlight several limitations to our proposal. The first is the small number of observations in our experimental study. It is therefore difficult to conduct secondary statistical analyses, such as assessing the reliability of postural data between the beginning and end of acquisition, examining the relationship between response quantity and correctness to unveil underlying strategies, and performing cluster analyses to define typical profiles. Nevertheless, all profiles are represented in our model, so our reduced sample size appears to be representative. The second limitation is that our proposed model is theoretical and depends heavily on the reproducibility of cognitive and motor measurements in ST and DT. This reliability is highly influenced not only by the individual [21] and task [8, 22, 23, 24] characteristics, but also by the prioritization of the task, dictated, among other things, by the instructions given [8, 21]; and beyond, their respect, which is difficult to ensure in a DT situation. In our study, the instructor gave no task prioritization during instructions to allow the expression of preferential strategies, although this is a known factor influencing postural performance [49, 50].

The choice of cognitive and motor tasks combined is also a key point. On the one hand, it is difficult to envisage "pure" cognitive or motor tasks (e.g. even in cognitive performance tests the subject must use fine motor skills to indicate their response). On the other hand, DT situations imply a black box area: it is difficult to know whether the effect of cognitive and motor tasks combined is equal to the combination of their isolated effects [3]. Questions then arise about the choice of tests to isolate and combine, which must be sufficiently 1) difficult to detect potential CMI while avoiding a floor effect; 2) sensitive to change therefore reliable and reproducible; 3) repeatable without causing any learning effect, and; 4) added or incorporated [51], 5) simple to modulate, making it possible to more effectively simulate ecological conditions, such as sending a text message while standing [52]. Finally, the notion of effect size, transfer of benefits, but above all clinical significance are rarely discussed regarding DT, although these points are essential to justify the relevance of an intervention. All these aspects will need to be substantiated or refuted by future studies to validate this model, but also strengthen our knowledge and understanding of DT assessments and interventions.

Statement and declaration

Authors' contribution

The authors confirm contribution to the paper as follows:

- MGG: concept, software development, writing.
- AVB: writing.
- SM: concept, writing.
- AP: concept, writing.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Competing Interests

None.

References

[1] Clémence Joubert and Hanna Chainay. Aging brain: the effect of combined cognitive and physical training on cognition as compared to cognitive and physical training alone–a systematic review. *Clinical Interventions in Aging*, 13:1267–1301, 2018.

[2] Oron Levin, Yael Netz, and Gal Ziv. The beneficial effects of different types of exercise interventions on motor and cognitive functions in older age: a systematic review. *European Review of Aging and Physical Activity*, 14:1–23, 2017.

[3] Xinyi Zhu, Shufei Yin, Minjia Lang, Rongqiao He, and Juan Li. The more the better? A meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults. *Ageing Research Reviews*, 31:67–79, 2016.

[4] Prudence Plummer, Lisa A Zukowski, Carol Giuliani, Amber M Hall, and David Zurakowski. Effects of physical exercise interventions on gait-related dual-task interference in older adults: a systematic review and meta-analysis. *Gerontology*, 62(1):94–117, 2015.

[5] Bruce Abernethy. Dual-task methodology and motor skills research: some applications and methodological constraints. *J Human Movement Studies*, 14:101–132, 1988.

[6] Galit Yogev-Seligmann, Jeffrey M Hausdorff, and Nir Giladi. The role of executive function and attention in gait. *Movement Disorders: Official Journal of the Movement Disorder Society*, 23(3):329–342, 2008.

[7] David J Clark. Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Frontiers in Human Neuroscience*, 9:246, 2015.

[8] Matthieu P Boisgontier, Iseult AM Beets, Jacques Duysens, Alice Nieuwboer, Ralf T Krampe, and Stephan P Swinnen. Age-related differences in attentional cost associated with postural dual tasks: increased recruitment of generic cognitive resources in older adults. *Neuroscience & Biobehavioral Reviews*, 37(8):1824–1837, 2013.

[9] Madli Bayot, Kathy Dujardin, Celine Tard, Luc Defebvre, Cédrick T Bonnet, Etienne Allart, and Arnaud Delval. The interaction between cognition and motor control: A theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning. *Neurophysiologie Clinique*, 48(6):361–375, 2018.

[10] Madli Bayot, Kathy Dujardin, Lucile Dissaux, Céline Tard, Luc Defebvre, Cédrick T Bonnet, Etienne Allart, Gilles Allali, and Arnaud Delval. Can dual-task paradigms predict falls better than single task? – a systematic literature review. *Neurophysiologie Clinique*, 50 (6):401–440, 2020.

[11] Louis Bherer, Arthur F Kramer, Matthew S Peterson, Stanley Colcombe, Kirk Erickson, and Ensar Becic. Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental Aging Research*, 34(3):188–219, 2008.

[12] AD Baddeley, S Della Sala, and C Gray. Testing central executive function with a pencil-and-paper test. In *Methodology of frontal and executive functions*, pages 61–80. Hove: Psychology Press, 1997.

[13] Prudence Plummer, Raymond M Villalobos, Moira S Vayda, Myriam Moser, and Erin Johnson. Feasibility of dual-task gait training for community-dwelling adults after stroke: A case series. *Stroke Research and Treatment*, 2014(1):e538602, 2014.

[14] Harold Pashler. Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, 116(2):220–244, 1994.

[15] Michel Lacour, Laurence Bernard-Demanze, and Michel Dumitrescu. Posture control, aging, and attention resources: models and posture-analysis methods. *Neurophysiologie Clinique/Clinical Neurophysiology*, 38(6):411–421, 2008.

[16] Elizabeth A Maylor and Alan M Wing. Age differences in postural stability are increased by additional cognitive demands. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 51(3): 143–154, 1996.

[17] Harold Pashler. Graded capacity-sharing in dual-task interference? *Journal of Experimental Psychology: Human Perception and Performance*, 20(2):330–342, 1994.

[18] Sabine Schaefer and Vera Schumacher. The interplay between cognitive and motor functioning in healthy older adults: findings from dual-task studies and suggestions for intervention. *Gerontology*, 57 (3):239–246, 2011.

[19] Menno Nijboer, Jelmer Borst, Hedderik van Rijn, and Niels Taatgen. Single-task fmri overlap predicts concurrent multitasking interference. *NeuroImage*, 100:60–74, 2014.

[20] David Navon and Jeff Miller. Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, 13(3):435–448, 1987.

[21] Prudence Plummer, Gail Eskes, Sarah Wallace, Clare Giuffrida, Michael Fraas, Grace Campbell, Kerry-Lee Clifton, Elizabeth R Skidmore, et al. Cognitive-motor interference during functional mobility after stroke: state of the science and implications for future research. *Archives of Physical Medicine and Rehabilitation*, 94(12): 2565–2574, 2013.

[22] Luca Prosperini, Letizia Castelli, Francesca De Luca, Francesca Fabiano, Ilaria Ferrante, and Laura De Giglio. Task-dependent deterioration of balance underpinning cognitive-postural interference in ms. *Neurology*, 87(11):1085–1092, 2016.

[23] Tara L McIsaac, Eric M Lamberg, and Lisa M Muratori. Building a framework for a dual task taxonomy. *BioMed Research International*, 2015(1):1–10, 2015.

[24] Olivier Beauchet and Gilles Berrut. Marche et double tâche: définition, intérêts et perspectives chez le sujet âgé. *Psychologie & NeuroPsychiatrie du Vieillissement*, 4(3):215–225, 2006.

[25] Bastiaan R Bloem, Yvette AM Grimbergen, J Gert van Dijk, and Marten Munneke. The "posture second" strategy: a review of wrong priorities in parkinson's disease. *Journal of the neurological sciences*, 248(1-2):196–204, 2006.

[26] Shmuel Springer, Nir Giladi, Chava Peretz, Galit Yogev, Ely S Simon, and Jeffrey M Hausdorff. Dual-tasking effects on gait variability: The role of aging, falls, and executive function. *Movement disorders: official journal of the Movement Disorder Society*, 21(7):950–957, 2006.

[27] M Gallou-Guyot, S Mandigout, L Bherer, and A Perrochon. Effects of exergames and cognitive-motor dual-task training on cognitive, physical and dual-task functions in cognitively healthy older adults: an overview. *Ageing research reviews*, 63:101135, 2020.

[28] Louis Bherer, Christine Gagnon, Antoine Langeard, Maxime Lussier, Laurence Desjardins-Crépeau, Nicolas Berryman, Laurent Bosquet, Thien Tuong Minh Vu, Sarah Fraser, Karen ZH Li, et al. Synergistic effects of cognitive training and physical exercise on dual-task performance in older adults. *The Journals of Gerontology: Series B*, 76(8): 1533–1541, 2021.

[29] Tom Delbroek, Wietse Vermeylen, and Joke Spildooren. The effect of cognitive-motor dual task training with the biorescue force platform on cognition, balance and dual task performance in institutionalized older adults: a randomized controlled trial. *Journal of Physical Therapy Science*, 29(7):1137–1143, 2017.

[30] Moran Dorfman, Talia Herman, Marina Brozgol, Shirley Shema, Aner Weiss, Jeffrey M Hausdorff, and Anat Mirelman. Dual-task training on a treadmill to improve gait and cognitive function in elderly idiopathic fallers. *Journal of Neurologic Physical Therapy*, 38(4): 246–253, 2014.

[31] Patrick Eggenberger, Vera Schumacher, Marius Angst, Nathan Theill, and Eling D de Bruin. Does multicomponent physical exercise with simultaneous cognitive training boost cognitive performance in older adults? a 6-month randomized controlled trial with a 1-year follow-up. *Clinical Interventions in Aging*, 10:1335–1349, 2015.

[32] S Falbo, G Condello, L Capranica, R Forte, and C Pesce. Effects of physical-cognitive dual task training on executive function and gait performance in older adults: a randomized controlled trial. *BioMed Research International*, 2016(1):1–12, 2016.

[33] Sarah A Fraser, Karen Z-H Li, Nicolas Berryman, Laurence Desjardins-Crépeau, Maxime Lussier, Kiran Vadaga, Lora Lehr, Thien Tuong Minh Vu, Laurent Bosquet, and Louis Bherer. Does combined physical and cognitive training improve dual-task balance and gait outcomes in sedentary older adults? *Frontiers in Human Neuroscience*, 10:1–12, 2017.

[34] EGA Karssemeijer, Willem JR Bossers, JA Aaronson, RPC Kessels, and MGM Olde Rikkert. The effect of an interactive cycling training on cognitive functioning in older adults with mild dementia: study protocol for a randomized controlled trial. *BMC Geriatrics*, 17:1–8, 2017.

[35] Hiroki Kayama, Kazuya Okamoto, Shu Nishiguchi, Minoru Yamada, Tomohiro Kuroda, Tomoki Aoyama, et al. Effect of a kinect-based exercise game on improving executive cognitive performance in community-dwelling elderly: case control study. *Journal of Medical Internet Research*, 16(2):e3108, 2014.

[36] Karen ZH Li, E Roudaia, M Lussier, L Bherer, A Leroux, and PA McKinley. Benefits of cognitive dual-task training on balance performance in healthy older adults. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences*, 65(12):1344–1352, 2010.

[37] Ying-Yi Liao, I-Hsuan Chen, Yi-Jia Lin, Yue Chen, and Wei-Chun Hsu. Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in older adults with mild cognitive impairment: a randomized control trial. *Frontiers in Aging Neuroscience*, 11:1–10, 2019.

[38] Shu Nishiguchi, Minoru Yamada, Takanori Tanigawa, Kaoru Sekiyama, Toshikazu Kawagoe, Maki Suzuki, Sakiko Yoshikawa, Nobuhito Abe, Yuki Otsuka, Ryusuke Nakai, et al. A 12-week physical and cognitive exercise program can improve cognitive function and neural efficiency in community-dwelling older adults: a randomized controlled trial. *Journal of the American Geriatrics Society*, 63 (7):1355–1363, 2015.

[39] Eva van Het Reve and Eling D de Bruin. Strength-balance supplemented with computerized cognitive training to improve dual task gait and divided attention in older adults: a multicenter randomized-controlled trial. *BMC Geriatrics*, 14:1–15, 2014.

[40] Hikaru Takeuchi, Daniele Magistro, Yuka Kotozaki, Kosuke Motoki, Keyvan Kashkouli Nejad, Rui Nouchi, Hyeonjeong Jeong, Chiho Sato, Salvatore Sessa, Ryoichi Nagatomi, et al. Effects of simultaneously performed dual-task training with aerobic exercise and working memory training on cognitive functions and neural systems in the elderly. *Neural Plasticity*, 2020:1–17, 2020.

[41] B Wollesen, S Schulz, L Seydell, and K Delbaere. Does dual task training improve walking performance of older adults with concern of falling? *BMC Geriatrics*, 17:1–9, 2017.

[42] Matthieu Gallou-Guyot, Stephane Mandigout, Romain Marie, Louise Robin, Jean-Christophe Daviet, and Anaick Perrochon. Feasibility and potential cognitive impact of a cognitive-motor dual-task training program using a custom exergame in older adults: A pilot study. *Frontiers in aging neuroscience*, 15:1–11, 2023.

[43] Laure Combourieu Donnezan, Alexandra Perrot, Sylvie Belleville, Frédéric Bloch, and Gilles Kemoun. Effects of simultaneous aerobic and cognitive training on executive functions, cardiovascular fitness and functional abilities in older adults with mild cognitive impairment. *Mental Health and Physical Activity*, 15:78–87, 2018.

[44] J Ridley Stroop. Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18(6):643–662, 1935.

[45] Matthieu Gallou-Guyot, Stéphane Mandigout, Patricia Sherley Almeida Prado, Romain Marie, Jean-Christophe Daviet, Anaick Perrochon, et al. Exergame and cognitive-motor dual-task training in the healthy elderly (income): a study protocol: Income study protocol. *European Rehabilitation Journal*, 2(1):1–10, 2022.

[46] Jean-Benoît Morin and Pierre Samozino. Interpreting power-force-velocity profiles for individualized and specific training. *International Journal of Sports Physiology and Performance*, 11(2):267–272, 2016.

[47] Anne G Copay, Brian R Subach, Steven D Glassman, David W Polly Jr, and Thomas C Schuler. Understanding the minimum clinically important difference: a review of concepts and methods. *The Spine Journal*, 7(5):541–546, 2007.

[48] Prudence Plummer and Gail Eskes. Measuring treatment effects on dual-task performance: a framework for research and clinical practice. *Frontiers in human neuroscience*, 9:1–7, 2015.

[49] Valerie E Kelly, Alexis J Eusterbrock, and Anne Shumway-Cook. Factors influencing dynamic prioritization during dual-task walking in healthy young adults. *Gait & posture*, 37(1):131–134, 2013.

[50] Thomas Muehlbauer, Hagen Voigt, Dennis Brueckner, and Rainer Beurskens. Effects of fixed versus variable task prioritization during short-term dual task practice on motor and cognitive task performance in young adults. *BMC Research Notes*, 15(1):1–5, 2022.

[51] Fabian Herold, Dennis Hamacher, Lutz Schega, and Notger G. Müller. Thinking while moving or moving while thinking – concepts of motor-cognitive training for cognitive performance enhancement. *Frontiers in Aging Neuroscience*, 10:1–11, 2018.

[52] Anne-Violette Bruyneel, Aline Reinmann, Simone C. Gafner, Jean-David Sandoz, and Noémie C. Duclos. Does texting while walking affect spatiotemporal gait parameters in healthy adults, older people, and persons with motor or cognitive disorders? a systematic review and meta-analysis. *Gait & Posture*, 100:284–301, 2023.