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Locomotor-cognitive dual-tasking is reduced in older adults relative to younger: A systematic review with meta-analysis

Jona Mustafovska *, Peter H. Wilson, Michael H. Cole, Thomas B. McGuckian

Healthy Brain and Mind Research Centre, School of Behavioural and Health Sciences, Faculty of Health Sciences, Australian Catholic University, 115 Victoria Parade, Fitzroy, Melbourne, VIC 3065, Australia

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ABSTRACT

Background: The capacity to dual-task is critically important over the lifespan, enabling an individual to respond to demands in their environment, both safely and efficiently.
Research question: Does recent evidence suggest that relative to younger adults, older adults are most disadvantaged when performing locomotor-cognitive dual-tasks under conditions that are more representative of the real-world?
Method: A literature search of major electronic databases was conducted to find relevant peer-reviewed papers published since 2011. Thirty-nine studies that compared proportional dual-task costs (pDTC) between older and younger adults on a locomotor-cognitive dual-task were included. Study quality was assessed using the Appraisal tool for Cross-Sectional Studies.
Results: pDTC were calculated for a total of 504 motor and 53 cognitive outcomes. Weighted means showed that older adults experienced larger pDTCs than younger adults for motor (mean difference = −6.97) and cognitive (mean difference = −8.15) outcomes. Velocity variability measures produced the largest group difference on motor pDTC (mean difference = −32.83), as did cognitive tasks that targeted arithmetic (mean difference = −18.57) and texting skills (mean difference = −17.43). Cognitive tasks that were 'most representative' resulted in the largest age differences on motor pDTC (mean difference = −16.89).
Significance: This meta-analysis showed that dual-tasking challenged the ability of older adults to maintain consistency in the sequential timing of their gait. As well, older adults demonstrated greater pDTCs on motor outcomes, especially when the cognitive tasks were more representative of day-to-day activities. Taken together, this suggests that clinical assessments should focus on measures of variability rather than absolute measures of temporal and spatial gait. It is recommended that future research use more representative paradigms that are sensitive to dual-task interference and predictive of real-world behaviour.

1. Background

Walking while performing another task at the same time is a key aspect of dual-tasking and an ability thought to decline with ageing. While a dual-task can be any combination of motor and cognitive task (e.g., motor-cognitive, motor-motor, cognitive-cognitive), motor-cognitive dual-tasks are exceedingly common in everyday life and of prime interest to research and clinical practice [1]. By definition, each component task has independent goals and measurable outcomes, e.g., walking a route while talking or texting [2]. Under novel or complex conditions, there is often interference between tasks when performed concurrently, such that performance on one or both tasks declines relative to single task performance; this is measured as a dual-task cost [DTC; 3]. Dual-task paradigms enable researchers and clinicians to build knowledge of changes in performance as a function of age and task constraints [4]. For older adults, there is a perception that dual-tasking declines with age, however, reported age trends are not always consistent [5,6]. It is also ideal that these dual-task paradigms are representative of real-world contexts; dual-task paradigms that resemble the demands and sometimes challenges of the real-world, are perceived as more reliable in informing clinical practice [7] and the design of dual-task training programs [8]. The review reported here will provide a current account of locomotor-cognitive dual-tasking in older adults. Our results will inform theory and predictions about older adults' functioning in an

* Corresponding author.
E-mail address: jona.mustafovska2@myacu.edu.au (J. Mustafovska).

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increasingly complex, information-driven world.

The most widely used theoretical framework that explains dual-task interference effects is the Multiple Resource Theory (MRT). The MRT posits that there are several independent pools of neural/processing resources that the performer can draw on when completing a dual-task [9–11], with the degree of interference dependent on competition for neural/processing resources at the level of each pool. More specifically, four dimensions account for interference effects observed in dual-task situations. The first dimension is the *stage of information processing* (e.g., sensory processing, perception, response selection, and response execution stages), with greater interference shown when both tasks enlist the same stage at the same time. The second dimension of *processing codes* has resources at each stage divided to process spatial and verbal information, separately. Interference is more likely to occur when two tasks use the same type of code (e.g., two tasks that both require verbal coding). The third dimension of *input modality* concerns the perceptual modality (visual, auditory, tactile, and olfactory) of the tasks; interference is less likely to occur in situations where two tasks require separate perceptual modalities [12]. Finally, the fourth dimension of *visual channel* distinguishes between focal and ambient vision. Interference here is less likely when two tasks require separate channels of vision. This theory has practical implications as it enables researchers and clinicians to predict the extent of dual-task interference according to the requirements of each task [12]. Further, it provides a thorough understanding of the impact of task demands on dual-task performance.

Dual-task performance is known to be influenced by the physical and neurological changes associated with ageing. For children, this can include maturation of brain structures (like prefrontal cortex) that support functional changes [13], whereas for older adults [i.e., aged 60 years and over; 14], this may include age-related decline in neural networks that underpin cognitive and motor control functions, and ultimately, performance [15]. More specifically, older adults experience structural changes to the brain that affect processing speed [16] and executive functions such as attention [17], working memory [18], and inhibition [19]. Moreover, the process of motor control becomes more reliant on executive functions with ageing, which further complicates the interference effects that are observed when motor and cognitive task are performed together [20]. Older adults tend to recruit additional (and bilateral) brain regions when performing motor and cognitive tasks to compensate for age-related decline in the sensorimotor system [see the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model; 21, 22]. Standard locomotor-cognitive dual-task paradigms have been the mainstay in ageing research, examining the biomechanics of gait (e.g., straight-line walking) while performing a cognitive task (e.g., counting backwards by 3) [23]. Recent studies have shown elevated cognitive-motor interference in older adults compared with younger, i.e., higher DTC for both cognitive (e.g., increased errors) and motor tasks (e.g., decreased walking speed) [24,25]. However, an earlier systematic review has suggested that the degree of interference appears to vary as a function of the type of cognitive task, and the level of processing required to complete the task [26]. Tasks that require participants to engage in a deeper level of cognitive processing (e.g., verbal fluency), compared with low-level sensory-motor processing (e.g., visual or auditory reaction time), tend to elicit greater costs on gait [10,26]. For example, tasks that involve internal interference [e.g., mental tracking like arithmetic; 27] are more likely to reduce cadence and walking speed than tasks that involve external interference (e.g., reaction time or discrimination tasks) [26]. Adult age differences might also be compounded by tasks that require concurrent processing of two streams of visual information, such as walking while texting [28], not to mention the dual motor demand of locomotor and manual performance [29].

Despite the breadth of research on the development of locomotor-cognitive dual-tasking, studies of ageing have suffered from low ecological validity, in terms of how well they both represent and generalise to everyday life contexts [30]. For example, most laboratory-based studies that focus on the impact of visual cognitive tasks on dual-task performance tend to present visual stimuli on desktop computers [31]. While this approach increases experimental validity, it limits eye gaze to a specific area of the room. In stark contrast, real-world behaviour often requires continuous monitoring of objects and events (across modalities) and responses to dynamic and ever-changing environmental demands [e.g., walking in heavy traffic while processing an important conversation; 32]. Past laboratory-based studies also utilise treadmills to represent overgrounding walking; this limits the generalisability of the results as treadmills provide different sensory information to walking in a real-world setting [33]. Indeed, research suggests that dual-task behaviour in the laboratory is very different to everyday life, both for gait [34] and cognition [35]. There are two aspects of ecological validity that are important to address in research protocols, namely verisimilitude and veridicality. Verisimilitude represents the extent to which the tasks performed in the research setting resemble tasks performed in the real world, whereas veridicality represents the extent to which task results in a research setting can be used to predict real world functioning [36–38]. A recent review highlighted the importance of considering both approaches when predicting real-world cognitive performance. For example, scores from executive functioning tests with verisimilitude were more closely related to cognitive performance than more traditional measures of executive functioning [37].

Earlier reviews of dual-tasking have shown high levels of dual-task interference across multiple parameters of gait and cognition in older adults [27,39]. Smith, Cusack, Cunningham and Blake [39] suggested that in comparison to single task performance, larger costs on walking speed, cadence, stride time, and stride time variability exhibited by healthy older adults under dual-task conditions reflected a greater risk of falls for this population. However, such reviews point to notable gaps in the literature about the type of locomotor-cognitive tasks tested. Both Wollesen, Wanstrath, van Schooten and Delbaere [27] and Smith, Cusack, Cunningham and Blake [39], for example, had insufficient studies for review that used texting as a secondary task.

Previous studies have focussed mainly on dual-task costs calculated as the raw score difference between single- and dual-task performance, as opposed to the more sensitive measure of *proportional dual-task costs* [pDTC; 27, 39]. pDTC considers single-task performance and, hence, provides a better estimate of the interference caused by dual-task conditions per se [40–44]. pDTC is represented as a percentage which enables a clear interpretation of the amount of interference caused by the dual-task. Further, unlike absolute costs, proportional costs are comparable across different age groups, task paradigms, and outcome measures [32]. While recent individual studies have compared pDTCs between adult age groups using cross-sectional designs [45–47], no systematic reviews or meta-analyses have directly compared older and younger adults on cognitive-motor dual-task performance. Further, recent studies also used more representative study protocols, for example by incorporating mobile phone use [48,49].

Clearly, a review of both gait and cognitive pDTC outcomes for locomotor-cognitive dual-tasks is required to improve our understanding of dual-task capacities in the ageing population. The aim of the combined systematic review and meta-analysis presented here was to synthesise research that compared dual-task interference between older and younger adults when performing locomotor and cognitive tasks concurrently, with a focus on pDTC as a measure of interference.

2. Methods

This systematic review and quantitative synthesis was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [50], and the study protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO; Registration number CRD42021253860).

2.1. Search strategy

A literature search of key databases (Scopus, CINAHL, Embase, MEDLINE, PsycINFO, Web of Science) was conducted using search terms structured around the following PICOS criteria: Population – healthy older adults aged 60 years and above, Intervention – locomotor-cognitive dual-task paradigms, Comparison – healthy younger adults, Outcome – motor and/or cognitive dual-task costs, and Study Design – cross-sectional and experimental [51]. The search string used for the systematic review follows: "dual task* " OR "multi task* " OR "secondary task* " OR "concurrent task* " AND aging OR ageing OR lifespan OR "older adult* " OR elder* OR "over 60 * " OR "adult age difference* " OR senior* AND walk* OR locomot* OR gait* . Given an earlier review by Beurskens & Bock [28] included papers published up to and including 2011, the current review sought to provide a more contemporary account and included papers published between May 2011 and February 2023. Search results were uploaded to Covidence where duplicates were automatically removed. All titles and abstracts were screened independently by two authors to identify potentially eligible papers. The full-text of remaining papers was then independently screened for eligibility by two authors using criteria described below. Conflicts in decisions were discussed by the two screeners and, where consensus was not reached, a third reviewer was involved in the process.

2.2. Eligibility criteria

To be eligible for inclusion, studies needed to meet the following criteria: (1) include a comparison between older adults (minimum age ≥ 60 years old) and younger adults (< 60 years old); (2) include sufficient data to calculate proportional dual-task costs (i.e., mean single-task and dual-task performance scores for both groups; (3) include a locomotor-cognitive dual-task paradigm; (4) include overground walking as the motor task; (5) have a publication date after 18th of May 2011; (6) be published in a peer-reviewed journal; and (7) be published in English. Studies were excluded if the target populations included participants with comorbid medical or neurological disorders that impact movement. Studies were also excluded if the study design was selected to assess the impact of an intervention on dual-task behaviour.

2.3. Data extraction

Data was extracted using a custom Excel™ Spreadsheet. Extracted data included basic descriptive information about the study (e.g., title, authors, publication year), the sample (e.g., sample size, age, and sex), study design, categorisation of both locomotor and cognitive tasks, and single- and dual-task performance results for older and younger groups. Tasks were categorised and coded according to locomotor and cognitive typologies. For example, spatial and temporal locomotor variables, and cognitive functions such as sustained attention/vigilance, word generation, and texting. See Table 1 for motor outcome categories.

Each cognitive task was also assigned to one of three categories: 'most representative', 'somewhat representative', and 'least representative'. The tasks were categorised according to their level of verisimilitude, that is, the extent to which they correspond to behaviour or actions that are performed in a daily life [52]. The 'most representative' category included tasks that emphasised the practical aspects of cognition and tasks that are routinely performed in daily life (e.g., texting). The 'somewhat representative' category consisted of tasks that contained some degree of familiarity but were not common encounters (e.g., counting backwards). Finally, the 'least representative' category included tasks that were not representative of real-world activities and could be considered 'novel' to the average person (e.g., serial subtractions).

2.4. Critical appraisal of study quality

Study reporting quality and risk of bias was assessed using the 20-item Appraisal tool for Cross-Sectional Studies (AXIS tool) [53]. Studies were assessed independently by two authors, and inconsistencies were resolved by including a third reviewer. To provide an overall score for each study, items assessed as 'yes/low risk' were awarded 1 point, items assessed as 'unclear/some concerns' were awarded 0.5 points, and items assessed as 'no/high risk' were awarded 0 points. Total scores greater than 15 were assessed as 'low risk' overall, total scores greater than 10 and less than or equal to 15 were assessed as 'some concerns' overall, and total scores less than or equal to 10 were assessed as 'high risk' overall.

2.5. Quantitative synthesis

R version 4.2.2 [54] was used to perform all quantitative synthesis. Group proportional dual-task costs were calculated for all motor and cognitive outcomes reported by the included studies. To ensure that performance reductions under dual-task conditions were always represented by a negative pDTC value, one of two pDTC formulae were used depending on the direction of favourable performance. For outcomes where a *lower* score was favourable, the below formula was used:

(single-task score - dual-task score) / single-task score x 100

For outcomes where a *higher* score was favourable, the below formula was used:

(dual-task score - single-task score) / single-task score x 100

Outliers, defined as values greater than ± 3 SD from the mean, were assessed separately for motor and cognitive pDTC and removed. The difference in pDTCs ($pDTC_{diff}$) between older and younger adults was

Table 1
Motor outcome categories.

Velocity	Velocity variability	Arm swing	Stability	Temporal	Temporal variability	Spatial	Spatial variability	Cadence
Velocity	Gait speed variability	Arm Swing Amplitude	Dynamic Stability	Step Time	Stride Time Variability	Step Length	Step Length Variability	Cadence
	Stride Velocity Variability	Arm Swing Asymmetry	Trunk Sway	Double Support Time	Step Time Variability	Step Width	Step Width Variability	
		Arm Swing Coordination	Trunk Sway Variability	Single Support Time	Double Support Time Variability	Stride Length	Stride Length Variability	
		Arm Swing Smoothness	Trunk Flexion	Stance Time	Single Support Time Variability	Minimum Foot Clearance Distance	Minimum Foot Clearance Variability	
		Trunk Rotation Amplitude	Trunk Roll	Swing Time	Stance Time Variability			
			Gait Coordination	Stride Time	Swing Time Variability			
			Trunk Rotation Smoothness	Step Time Change Stance				

used to compare pDTCs between groups. To ensure uneven sample sizes did not disproportionately influence synthesised results, weighted means for each comparison, weighted by total sample size, were calculated using the '*weighted.mean*' function from the '*stats*' package [54].

For motor pDTC$_{diff}$, older vs younger comparisons were performed according to locomotor outcome categories, cognitive task categories, and cognitive task representativeness. For cognitive pDTC$_{diff}$, older vs younger comparisons were performed according to the cognitive outcome categories and cognitive task representativeness. Significance was determined by 95 % CI that did not cross zero. To assess between study homogeneity, Levene's tests were run for each category that included more than one study. When Levene's test was significant, distribution of the pDTC$_{diff}$ outcomes was investigated to determine which studies may be unevenly distributed, and if there was a conceptual reason to remove the studies from the weighted mean. In all cases, there was no sound conceptual reason to exclude studies, and all studies were retained in the analysis.

3. Results

3.1. Study characteristics

A total of 4958 records were initially retrieved and, after removing duplicates, 2602 unique records were then screened. During title and abstract screening, 2251 studies were excluded, resulting in 351 studies for full-text review. Of these studies, twenty-two could not be retrieved, and 290 were excluded following full-text review, resulting in a final sample of 39 eligible studies. The screening process is shown in Fig. 1.

Demographic information relating to study participants, including sample size, % women, and mean (SD) age for younger and older groups, is presented in Supplementary Material 1. In total, 2561 participants were included (1186 older adults, 1375 younger adults), and sample size ranged from 14 to 440 participants. The mean (SD) age of older participants was 71.1 (2.6) years and 25.9 (5.2) years for younger participants.

3.2. Types of locomotor-cognitive dual-tasks

Study characteristics, including the cognitive tasks used, motor and cognitive outcomes, stimulus presentation, response, DTC calculation method used, and main findings for each included study are presented in Table 2. For cognitive tasks, the most often used tasks were serial subtractions 3 (31 % of studies), serial subtractions 7 (13 %), word generation tasks (13 %), Stroop tasks (10 %), and texting tasks (10 %). All other cognitive tasks were used in less than 10 % of studies. Stimuli were presented visually (15 % of studies), auditorily (18 % of studies), or with other methods (72 % of studies). The 'other' category mainly consisted of tasks where a singular prompt was provided at the beginning of the condition (e.g., starting number for serial subtractions 3). Most studies required a verbal response (79 % of studies), while 13 % of studies required manual responses and 8 % required both verbal and manual responses.

3.3. Critical appraisal of study quality

A summary of study reporting quality and risk of bias is presented in Fig. 2. AXIS ratings for each study are provided in Supplementary Material 2. Overall, the quality of methodological reporting and risk of bias was rated as 'low risk' for 13 studies (33 %), 'some concerns' for 25 studies (64 %), and 'high risk' for 1 study (3 %). Specifically, in the reporting of most studies, there were clear aims (item 1, 92 %), an appropriate study design was described (item 2, 100 %), results were presented for all analyses (item 16, 97 %), results were appropriately discussed (item 17, 97 %), and ethical approval was reported (item 20, 97 %). Most studies (82 %) did not justify sample size (item 3), and most studies did not clearly address items relating to obtaining a representative sample (items 5 (59 %) and 6 (51 %)). No studies reported information related to; (a) measures undertaken to address and categorise non-responders (item 7); (b) the response rate, raising concerns about non-response bias (item 13); or (iii) non-responders (if appropriate; item 14).

3.4. Quantitative synthesis

Many dual-task studies did not report pDTC outcomes, instead favouring absolute DTC or only reporting raw scores for single- and dual-tasks. Due to this limitation, pDTCs were calculated for these studies using group mean single- and dual-task performance. To ensure the validity of this approach, separately for older and younger adult groups, t-tests were conducted to compare reported pDTC to calculated pDTC for outcomes from studies that reported both pDTC and single- and dual-task performance. The results of the t-tests were non-significant for both older adults ($p = 0.884$) and younger adults ($p = 0.291$), indicating that there was no difference between the reported pDTC and calculated pDTC. Therefore, calculated pDTC were used for the remainder of analyses. Group mean pDTC for the older and younger groups are reported in Supplementary Material 3.

3.4.1. Locomotor pDTC

A total of 11 outliers (± 3 SD from the mean) were removed (3 Arm Swing Asymmetry; 5 Temporal Variability, 1 Stability, and 2 outcomes belonging to Other), resulting in a total of 504 locomotor pDTC$_{diff}$ outcomes from 38 studies. The overall weighted mean (95 % CI) for all outcomes was −6.97 (-8.26; −5.69), indicating that across locomotor outcomes, older adults demonstrated a pDTC that was approximately 7 % larger than younger adults.

The locomotor outcomes that resulted in the largest pDTC$_{diff}$ between younger and older adults (see Fig. 3) were velocity variability (older adults 33 % larger pDTC), stability (older adults 14 % larger pDTC), and temporal variability (older adults 14 % larger pDTC). Cadence, spatial, temporal, spatial variability, arm swing, and velocity outcomes also demonstrated larger pDTCs for older adults, ranging between 2 % and 13 %.

The locomotor pDTC$_{diff}$ according to the cognitive task are presented in Fig. 4. The cognitive secondary tasks that resulted in the largest pDTC$_{diff}$ between younger and older adults were the arithmetic tasks (older adults 19 % larger pDTC), texting tasks (17 %), and Stroop tasks (13 %). Serial subtractions 3, serial subtractions 7, spontaneous speech task, sustained attention/vigilance tasks, and word generation tasks also demonstrated a larger pDTCs for older adults, ranging between 3 % and 9 %. In contrast, auditory processing speed, auditory choice reaction time, counting backwards, reciting alternate letters of the alphabet, and recognition memory were not different between younger and older adults.

The locomotor pDTC$_{diff}$ according to representativeness of the cognitive task is presented in Fig. 5. The category that resulted in the largest pDTC$_{diff}$ between younger and older adults included the tasks that were 'most representative' (17 %). Tasks that were 'somewhat representative' and 'least representative' of day-to-day tasks also produced a difference between older and younger adults (6 % for both).

3.4.2. Cognitive pDTC

Three outliers were removed, resulting in 53 cognitive pDTC$_{diff}$ outcomes from 11 studies. The overall weighted mean (95 % CI) for all outcomes was –8.15 (-11.51; −4.78), indicating that older adults demonstrate larger pDTC than younger adults.

Cognitive pDTC$_{diff}$ according to the cognitive outcome category is presented in Fig. 6. Tasks that targeted auditory processing speed and texting tasks demonstrated the largest difference in pDTC, with older adults showing 25 % and 7 % larger pDTC than younger adults, while the remaining tasks showed no difference.

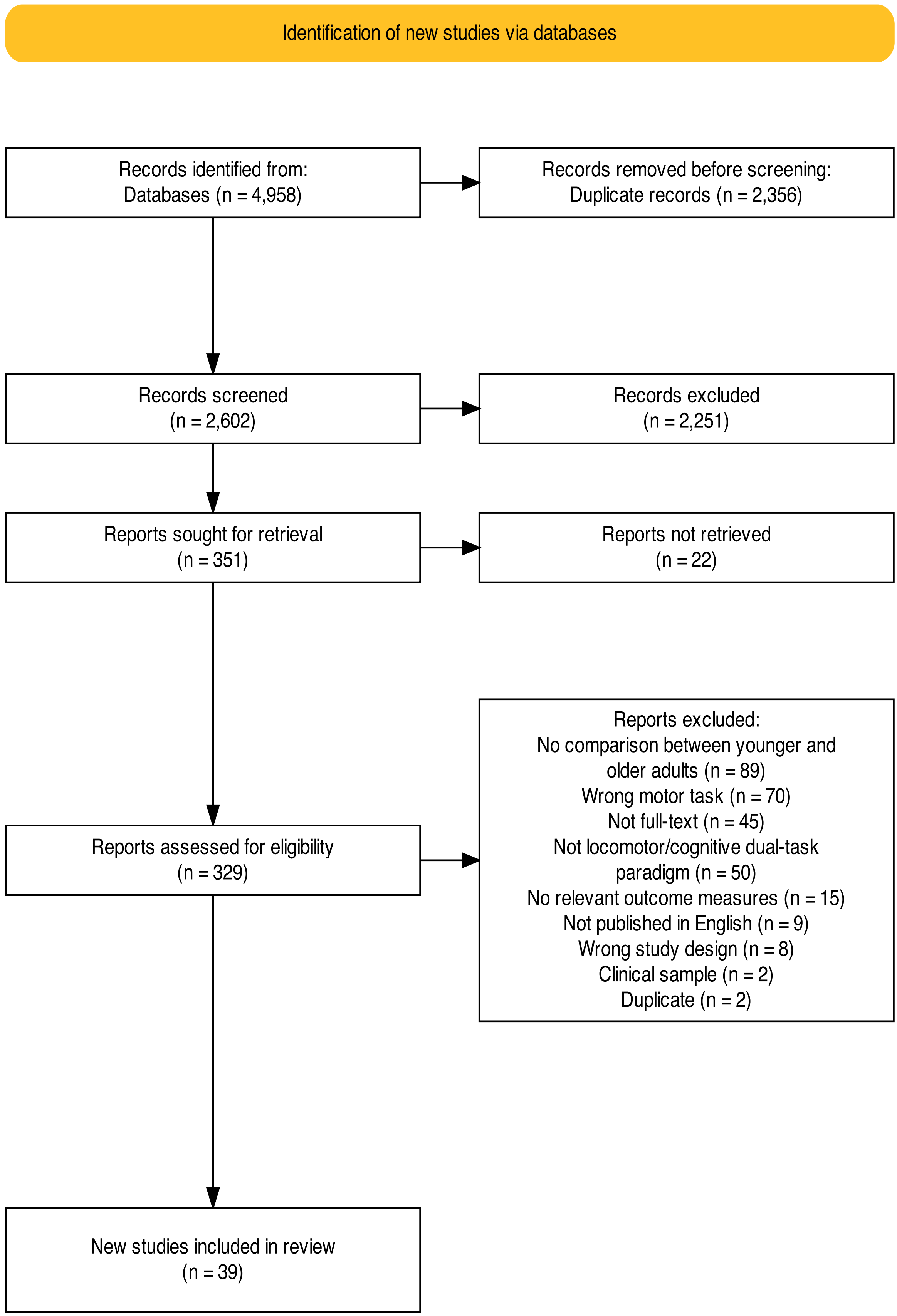

Fig. 1. PRISMA flow diagram.

Table 2
Study characteristics and dual-task findings.

Author (year)	Cognitive task	Stimulus presentation	Response	Motor outcomes[a]	Cognitive outcomes	DTC calculation method	Dual-task findings
Alapatt, Peel, Reid, Gray and Hubbard [48]	Texting	Visual	Manual	Velocity (43)	-	-	OA (≥60 years) were slower on gait speed vs. 50–59, 40–49, 30–39 & 20–29 age groups.
Asai, Doi, Hirata and Ando [55]	Serial Subtractions 7	Other	Vocal	Stability (9) Temporal Variability (32) Velocity (43)	-	-	OA walked slower than YA.
Asai, Oshima, Fukumoto, Kubo, Koyama and Misu [56]	Counting Backwards	Other	Vocal	Spatial (22, 27) Spatial Variability (23, 28) Stability (41, 42) Temporal (24) Temporal Variability (26) Velocity (43)	-	DT-change	OA walked slower than YA.
Behrens, Mau-Moeller, Lischke, Katlun, Gube, Zschorlich, Skripitz and Weippert [57]	Serial Subtractions 3	Other	Vocal	Spatial (22, 29) Spatial Variability (23, 30) Temporal (7, 17, 20, 24, 34) Temporal Variability (8, 18, 21, 26, 35) Velocity (43) Velocity Variability (11)	-	-	OA showed more gait variability after mentally fatiguing task vs. YA.
Belur, Hsiao, Myers, Earhart and Rawson [49]	Texting Word Generation Tasks	Other	Manual Vocal	Cadence (5) Spatial (29) Velocity (43)	-	pDTC	OA had higher DTCs (velocity, stride length) vs. YA.
Bianchini, Warmerdam, Romijnders, Hansen, Pontieri and Maetzler [58]	Choice Reaction Time (Visual) Stroop task Visual Processing Speed	Visual	Manual Vocal	-	Response time	pDTC	No significant age-related differences in performance for both cognitive tasks.
Brach, McGurl, Wert, Vanswearingen, Perera, Cham and Studenski [59]	Reciting Alternate Letters of the Alphabet	Other	Vocal	Stability (9) Velocity (43)	-	-	OA walked less smoothly and slower vs. YA.
Brustio, Magistro, Zecca, Rabaglietti and Liubicich [60]	Serial Subtractions 3	Other	Vocal	Velocity (43)	Average Correct Response Rate	-	OA (65–85 years) had more gait decrements vs. 40–55 & 20–35 age groups. OA had higher costs (motor and cognitive) vs. YA.
Chen and Chou [61]	Recognition Memory Tasks	Auditory	Vocal	Spatial (27) Stability (9) Velocity (43)	Accuracy (%) Reaction time (ms)	-	No significant age-related differences in gait velocity.
Deshpande, Hewston and Yoshikawa [62]	Serial Subtractions 3	Other	Vocal	Stability (38) Velocity (43)	-	-	No significant age-related differences in gait speed. OA showed significant trunk roll decrease with Galvanic Vestibular Stimulation (GVS).
Dommes [63]	Auditory Processing Speed Visual Processing Speed Visual Processing Speed & Auditory Processing Speed	Other	Manual	Velocity (43)	Mean Reaction Time Omissions	-	Older-old adults (73–82 years) and younger-old (60–72 years) adults showed more street-crossing collisions and longer reaction times vs. YA (19−26).
Goh, Pearce and Vas [45]	Auditory Processing Speed Choice Reaction Time (Auditory) Recall Memory Tasks Serial Subtractions 3 Serial Subtractions 7	Auditory Other	Vocal	Velocity (43)	Correct recall rate Number of correct responses Number of words generated Reaction time (ms)	pDTC	Higher cognitive task difficulty (reaction-time task) increased OAs DTC in gait speed, not YA. Higher cognitive task difficulty (counting backwards) increased YAs DTC, not OA.

(continued on next page)

Table 2 (*continued*)

Author (year)	Cognitive task	Stimulus presentation	Response	Motor outcomes[a]	Cognitive outcomes	DTC calculation method	Dual-task findings
Gorecka, Vasylenko and Rodríguez-Aranda [64]	Word Generation Tasks Choice Reaction Time (Auditory) Stroop task	Auditory	Vocal	Spatial (22, 27) Spatial Variability (23, 28) Velocity (43) Velocity Variability (11)	-	-	Both age groups showed DTCs in gait when tending to specific ear. YA showed greater costs to step length vs. OA.
Granacher, Bridenbaugh, Muehlbauer, Wehrle and Kressig [65]	Serial Subtractions 3	Other	Vocal	Spatial Variability (30) Temporal Variability (32) Velocity Variability (33)	-	-	OA showed more stride-to-stride variability and centre-of-pressure displacements vs. YA.
Hamacher, Hamacher, Herold and Schega [66]	Serial Subtractions 3	Other	Vocal	Spatial (12, 29) Spatial Variability (13, 30) Temporal (31) Temporal Variability (32)	-	-	OA showed lower average minimum foot clearance vs. YA.
Hamacher, Hamacher, Müller, Schega and Zech [67]	Serial Subtractions 7	Other	Vocal	Spatial (12, 29) Spatial Variability (13, 30) Temporal (31) Temporal Variability (32) Velocity (43)	Number of correct responses	-	Relevant outcomes were presented, but not discussed or described.
Hassan, Bonetti, Kasawara, Beal, Rozenberg and Reid [46]	Backward Spelling	Other	Vocal	Velocity (43)	Number of words attempted Spelling backwards accuracy	pDTC	OA showed larger decrements in gait velocity vs. YA.
Hennah, Ellis and Doumas [68]	Recognition Memory Tasks	Auditory	Vocal	Spatial (22, 27, 29) Temporal (24) Velocity (43)	Accuracy	pDTC	OA showed larger DTCs in step width vs. YA. No significant age-related differences in DTC in gait speed, stride length and step times.
Hernandez, Winesett, Federico, Williams, Burke and Clark [69]	Recognition Memory Tasks	Visual	Vocal	Temporal (25)	Number of mistakes or indecisions	-	OA walked slower than YA before turning.
Hsieh and Cho [70]	Digit Span Stroop task	Other	Vocal	Spatial (22) Stability (37) Velocity (43)	-	-	OA had decreased walking velocity and increased stance/swing time; YA showed little to no difference.
Hupfeld, Geraghty, McGregor, Hass, Pasternak and Seidler [71]	Serial Subtractions 7	Other	Vocal	Temporal Variability (26) Velocity (43)	Accuracy Number attempted	pDTC	OA showed larger DTCs (gait speed & gait variability) vs. YA.
Klotzbier, Wollesen, Vogel, Rudisch, Cordes, Jöllenbeck and Vogt [72]	Word Generation Tasks	Other	Vocal	Cadence (5) Spatial (29) Temporal (7, 17, 19) Velocity (43)	-	pDTC	Significant age differences in stride length, single limb support and double limb support.
Krasovsky, Weiss and Kizony [73]	Texting	Visual	Manual	Spatial (29) Spatial Variability (30) Temporal (31) Temporal Variability (32) Velocity (43)	Texting accuracy Texting speed (characters per minute)	pDTC	In outdoor setting, OA showed larger DTCs (gait, gait variability, texting accuracy) vs. YA. No significant age-related differences in motor (indoor setting) and cognitive DTCs.
Krishnan, Cho and Mohamed [74]	Serial Subtractions 3	Other	Vocal	Cadence (5) Spatial (22, 27, 29) Temporal (7, 31)	Number of correct responses	pDTC	OA showed greater motor DTCs vs. YA. No significant age-related difference in cognitive DTC (number of correct responses).

(*continued on next page*)

Table 2 (*continued*)

Author (year)	Cognitive task	Stimulus presentation	Response	Motor outcomes[a]	Cognitive outcomes	DTC calculation method	Dual-task findings
				Temporal Variability (32) Velocity (43)			
Lau, Mallya, Pang, Chen, Abdul Jabbar, Seah, Yap, Ng and Wee [47]	Serial Subtractions 7	Other	Vocal	Cadence (5) Spatial (22, 27) Temporal (7) Velocity (43)	-	pDTC	Older men showed greater DTC (gait speed, step length and double support time) vs. younger men. For younger and older women, no age-related differences observed in the preceding outcomes. No significant age-related difference in DTC in cadence and stride width for both genders.
Lohnes and Earhart [75]	Word Generation Tasks	Other	Vocal	Cadence (5) Spatial (29) Velocity (43)	-	-	OA showed more gait decrements vs. YA.
Mirelman, Bernad-Elazari, Nobel, Thaler, Peruzzi, Plotnik, Giladi and Hausdorff [76]	Serial Subtractions 3	Other	Vocal	Arm Swing (1, 2, 3, 4, 39) Spatial (22) Stability (10, 40) Temporal Variability (32) Velocity (43)	-	-	OA (61–77 years) showed greater increase in gait variability vs. 30–40, 41–50 & 51–60 age groups. Older age groups showed increased arm swing asymmetry vs. younger age groups.
Mirelman, Maidan, Bernad-Elazari, Shustack, Giladi and Hausdorff [77]	Serial Subtractions 3	Other	Vocal	Spatial (29) Spatial Variability (30) Velocity (43)	-	-	OA walked slower and showed shorter stride length vs. YA.
Nóbrega-Sousa, Gobbi, Orcioli-Silva, Conceição, Beretta and Vitório [78]	Sustained Attention / Vigilance	Other	Vocal	Spatial (22, 27) Spatial Variability (23, 28) Temporal (24) Temporal Variability (26) Velocity (43) Velocity Variability (11)	-	-	OA showed greater step length variability vs. YA.
Plummer-D'Amato, Brancato, Dantowitz, Birken, Bonke and Furey [79]	Stroop task Visuospatial Decision-Making Tasks	Auditory Other	Vocal	Velocity (43)	-	pDTC	When instructed to 'walk as fast as you can', OA showed greater DTCs on gait speed vs. YA (clock task).
Pothier, Benguigui, Kulpa and Chavoix [80]	Visual Tracking	Visual	Manual	Velocity (43)	-	-	YA walked faster vs. 60–74 & 75 + age groups.
Protzak, Wiczorek and Gramann [24]	Visual Processing Speed	Visual	Manual	Velocity (43)	Percentage of false responses Percentage of misses Response time	-	OA showed greater DTCs on % of correct responses vs. YA. No significant age-related differences in DTC on walking speed.
Prupetkaew, Lugade, Kamnardsiri and Silsupadol [81]	Spontaneous Speech Task Texting	Auditory	Manual Vocal	Cadence (5) Spatial (22) Temporal (24) Velocity (43)	Accuracy - % correct Rate of response	DT-change	OA showed greater gait decrements (walking velocity, step time, step length, cadence) vs. YA in both tasks.
Sasaki, Ooi, Yokota, Azuma, Asano and Yadai [82]	Recall Memory Tasks Serial Subtractions 3 Simple Counting	Other	Vocal	Spatial (6)	-	DT-change pDTC	OA showed greater DTCs vs. YA.
Soangra and Lockhart [83]	Serial Subtractions 3	Other	Vocal	Spatial (12, 22, 27) Temporal (7, 17, 24, 31, 34) Velocity (43)	-	-	Both age groups showed decreased step length and increased double-support time and mean single stance time. OA showed higher linear variability in step width, heel contact velocity, double-support time, mean single stance time and gait cycle time.
St George, Jayakody, Healey, Breslin, Hinder and Callisaya [84]	Reciting Alternate Letters of the Alphabet	Other	Vocal	Velocity (43)	Cognitive performance on RAL Cognitive	-	Relevant outcomes were presented, but not discussed or described.

(*continued on next page*)

Table 2 (*continued*)

Author (year)	Cognitive task	Stimulus presentation	Response	Motor outcomes[a]	Cognitive outcomes	DTC calculation method	Dual-task findings
	Serial Subtractions 3				performance on SS3		
Uematsu, Tsuchiya, Suzuki and Hortobágyi [85]	Arithmetic Tasks	Other	Vocal	Spatial (22) Stability (9) Velocity (43)	-	pDTC	OA showed greater DTCs (walking distance, walking velocity) vs. YA.
Wellmon, Barr-Gillespie, Newton, Ruchinskas and Stephens [86]	Auditory Processing Speed	Auditory	Vocal	Cadence (5) Velocity (43)	Mean voice reaction time	-	OA showed greater decrements in cognitive performance vs. younger and middle-aged adults.
Yogev-Seligmann, Giladi, Gruendlinger and Hausdorff [87]	Word Generation Tasks	Other	Vocal	Temporal (31) Temporal Variability (32) Velocity (43)	Number of words generated while seated Number of words generated while standing	DT-change	No significant age-related differences in gait variables (average stride time, stride time variability & walking speed).

[a]Specific Motor Outcomes: 1 = Arm Swing Amplitude; 2 = Arm Swing Asymmetry; 3 = Arm Swing Coordination; 4 = Arm Swing Smoothness; 5 = Cadence; 6 = Distance; 7 = Double Support Time; 8 = Double Support Time Variability; 9 = Dynamic Stability; 10 = Gait Coordination; 11 = Gait Speed Variability; 12 = Minimum Foot Clearance; 13 = Minimum Foot Clearance Variability; 14 = Number of Minimum Toe Clearances; 15 = Number of swing phase; 16 = Required Coefficient of Friction; 17 = Single Support Time; 18 = Single Support Time Variability; 19 = Stance; 20 = Stance Time; 21 = Stance Time Variability; 22 = Step Length; 23 = Step Length Variability; 24 = Step Time; 25 = Step Time Change; 26 = Step Time Variability; 27 = Step Width; 28 = Step Width Variability; 29 = Stride Length; 30 = Stride Length Variability; 31 = Stride Time; 32 = Stride Time Variability; 33 = Stride Velocity Variability; 34 = Swing Time; 35 = Swing Time Variability; 36 = Transverse Coefficient of Friction; 37 = Trunk Flexion; 38 = Trunk Roll; 39 = Trunk Rotation Amplitude; 40 = Trunk Rotation Smoothness; 41 = Trunk Sway; 42 = Trunk Sway Variability; 43 = Velocity
OA = Older Adults / YA = Younger Adults / DTC(s) = Dual-task cost(s)

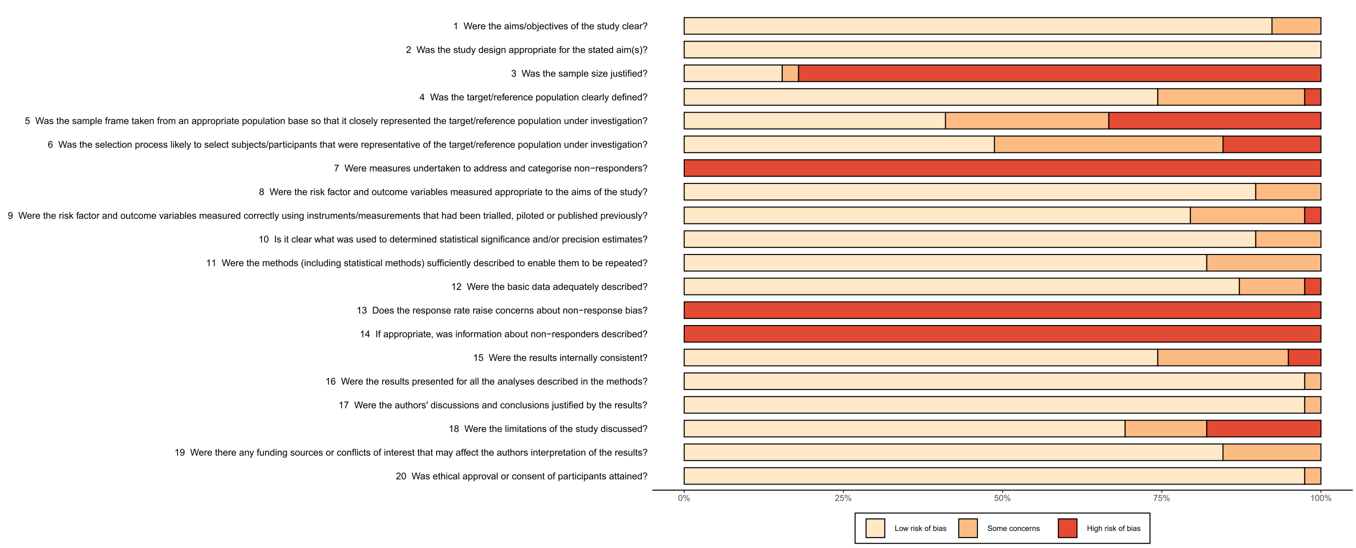

Fig. 2. Summary of AXIS critical appraisal of study reporting quality and risk of bias.

The cognitive $pDTC_{diff}$ according to representativeness of the cognitive secondary task is presented in Fig. 7. The category that resulted in the largest $pDTC_{diff}$ between younger and older adults were the tasks that were 'somewhat representative' (17 %). Tasks that were 'most representative' of day-to-day tasks also produced a difference between older and younger adults (7 %), while tasks were 'least representative' did not produce a difference between younger and older adults.

4. Discussion

The aim of the current review was to synthesise research that compared older and younger adults' proportional dual-task costs when performing locomotor-cognitive dual-tasks. A total of 39 studies were included, 38 of which contributed 504 locomotor pDTC outcomes, and 11 of which contributed 53 cognitive pDTC outcomes. Overall, older adults demonstrated approximately 7 % larger pDTCs than younger adults, indicating greater dual-task interference in the older population. In what follows, we interpret the pattern of findings as a function of task type and outcome metric. Further, this discussion will interpret the significance of these findings in relation to the representativeness of tasks and provide recommendations for clinicians and researchers in the field of ageing and dual-task research.

Larger $pDTC_{diff}$ values were found for gait variability outcomes (i.e., spatial variability, temporal variability, and velocity variability), compared with non-variability equivalents (i.e., spatial, temporal, and velocity, respectively). Older adults showed approximately 14 % larger pDTCs for temporal variability outcomes than younger adults, suggesting that dual-task situations may present substantial challenges for an older adult's ability to maintain consistency in the sequential timing of their gait (i.e., step-to-step variability and stride-to-stride variability). Specifically, in older adults, dual-tasking increased variability to a level that is often observed in people who have previously fallen and are at risk of falling [88]. This suggests that imposition of a secondary task in

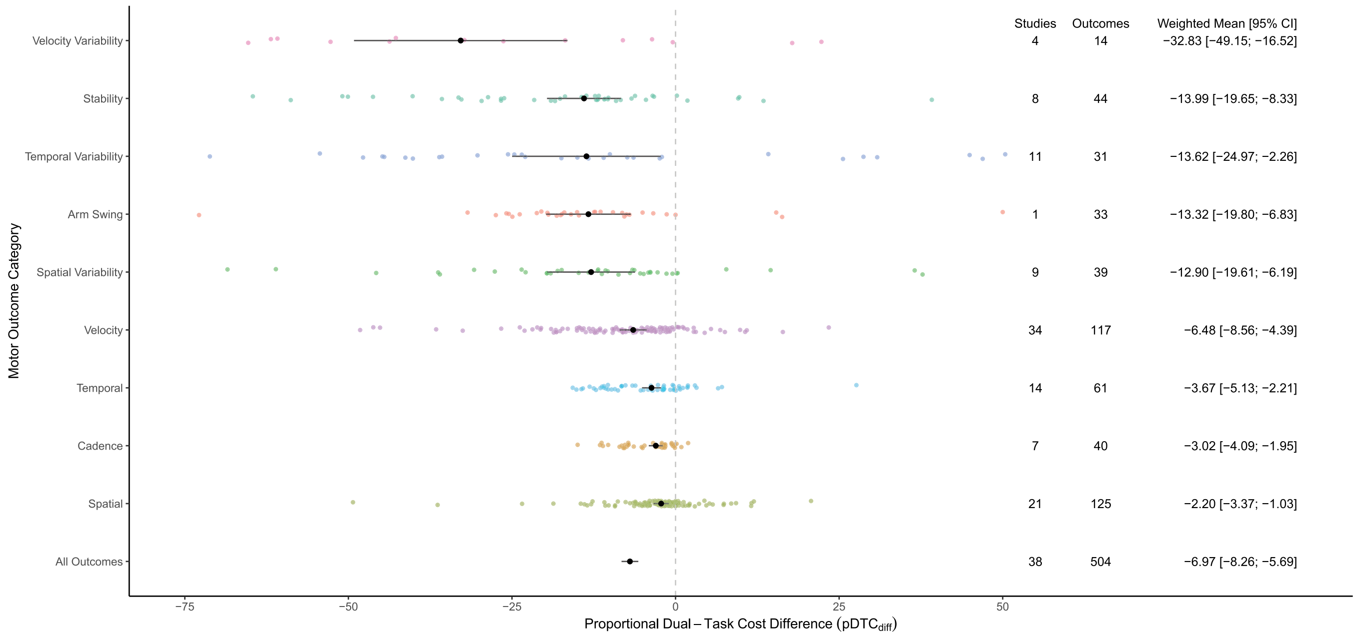

Fig. 3. Average motor $pDTC_{diff}$ results according to gait outcome measures. Fig. 3 *Legend.* This figure presents motor pDTC according to broad motor outcomes. These broad outcomes consist of more specific groupings. Arm swing includes arm swing amplitude, arm swing asymmetry, arm swing coordination, arm swing smoothness, trunk rotation amplitude; Spatial includes distance, minimum foot clearance, step length, step width, and stride length; Spatial variability includes step length variability, step width variability, stride length variability, minimum foot clearance variability; Stability includes dynamic stability, gait coordination, trunk flexion, trunk roll, trunk rotation smoothness, trunk sway, trunk sway variability; Temporal includes double support time, single support time, stance, stance time, step time, step time change, stride time, swing time; Temporal variability includes double support time variability, single support time variability, stance time variability, step time variability, stride time variability, swing time variability; Velocity includes velocity; Velocity variability includes gait speed variability, stride velocity variability; Other includes required coefficient of friction, transverse coefficient of friction, number of swing phases, number of minimum toe clearances.

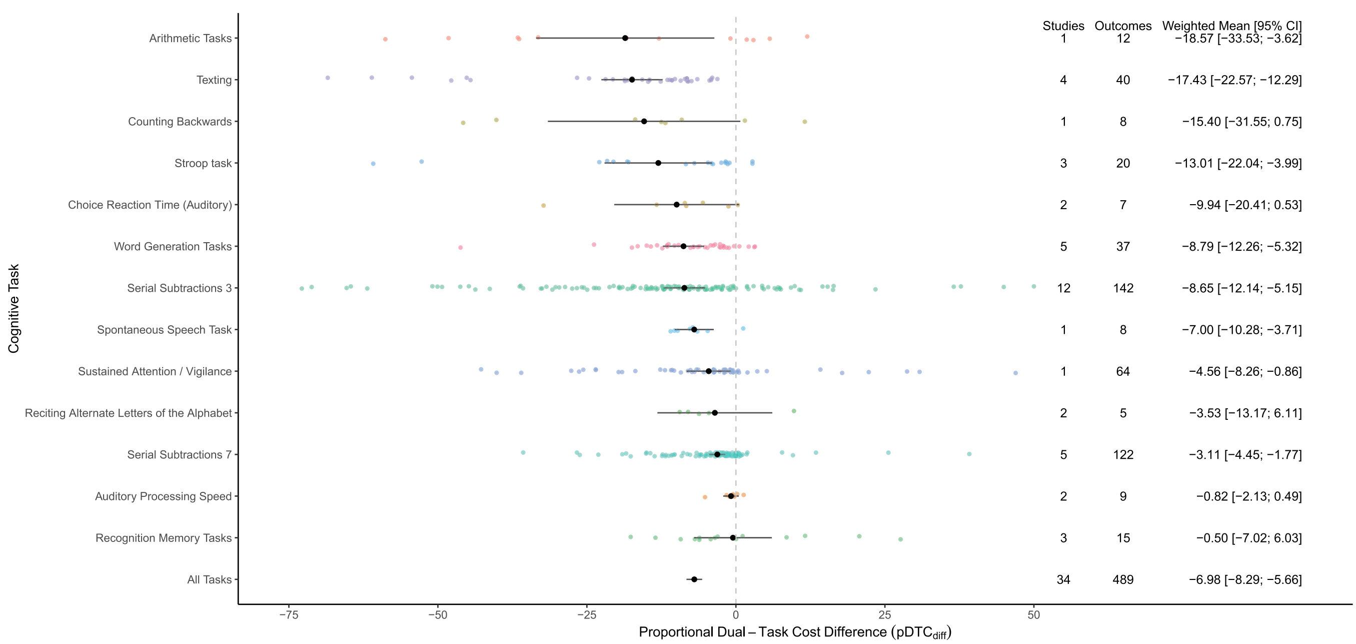

Fig. 4. Average motor $pDTC_{diff}$ results as a function of the cognitive task.

healthy older adults may potentially impose a risk similar to what is observed in at-risk fallers during single motor task performance [89]. It is therefore recommended that clinicians working in geriatrics focus their assessment on measures of variability rather than absolute measures of temporal and spatial gait, as the changes in variability are substantial and may enable clinicians to easily identify those who are at greatest risk of an adverse event while multi-tasking [90]. Dual-task training, whereby ecologically valid cognitive tasks are used in training along with motor tasks such as gait or balance, may be a valuable avenue to address this issue, as they have been shown to result in favourable outcomes for older adults [5] and those with Parkinson's disease [91].

However, when considering these gait variability outcomes, it is important to note that some aspects of variability are beneficial and provide a degree of adaptability and flexibility to our movement patterns, while other aspects are non-functional and can lead to poor

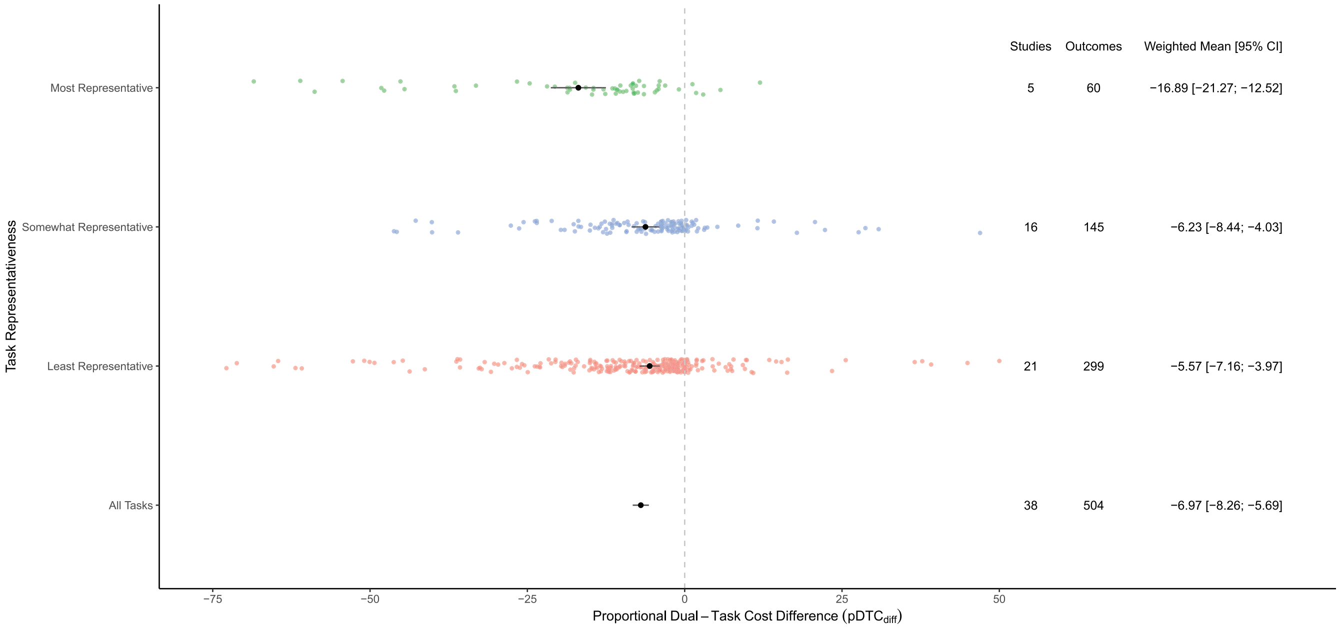

Fig. 5. Average motor pDTC$_{diff}$ results as a function of task representativeness. Fig. 5 *Legend.* This figure presents motor pDTC according to task representativeness. The 'most representative' category consists of texting, spontaneous speech task, arithmetic tasks; 'Somewhat representative' category consists of visual processing speed, auditory processing speed, simple counting, word generation tasks, counting backwards, recall tasks, recognition tasks, visual tracking tasks, sustained attention/vigilance tasks, digit span; 'Least representative' category includes choice reaction time (visual), choice reaction time (auditory), serial subtractions, backward spelling, reciting alternate letters of the alphabet, Stroop tasks, visuospatial decision tasks.

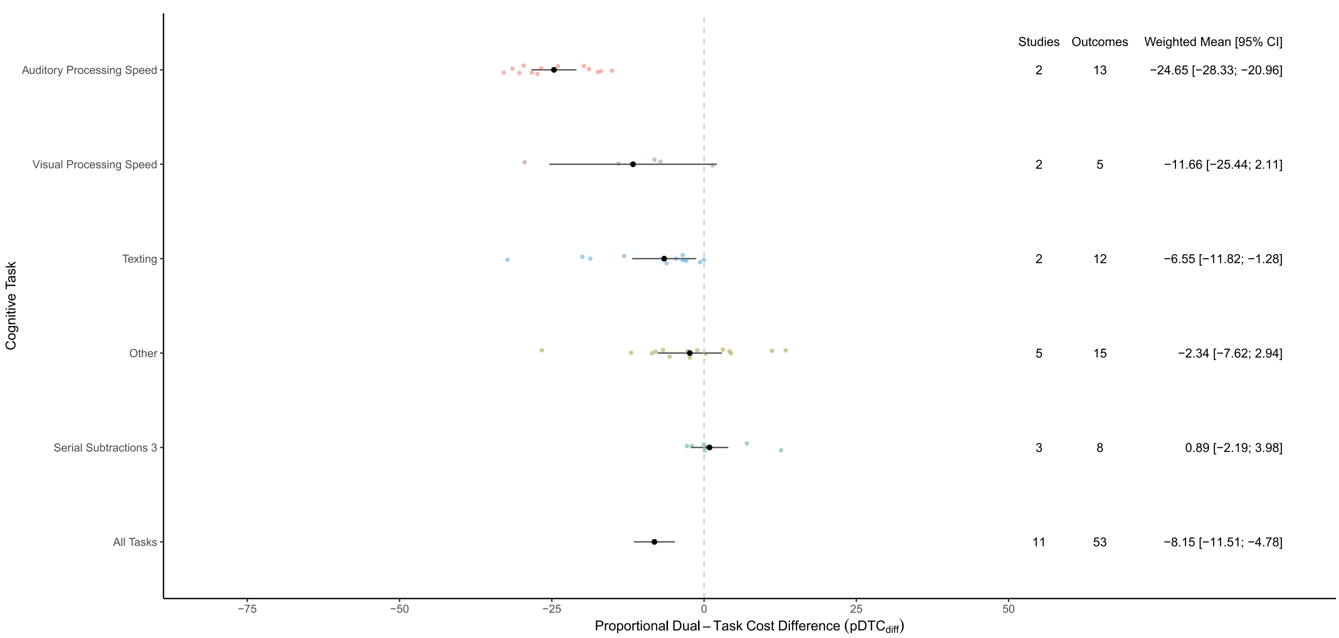

Fig. 6. Average cognitive pDTC$_{diff}$ results as a function of the cognitive task.

balance control [92]. In the current study, while older adults demonstrated greater levels of variability compared with their younger counterparts, it is plausible that a significant proportion of that variability was non-functional [93,94]. It is likely that older adults experience an increase in non-functional variability at the expense of functional variability due to age-related changes to the peripheral and central nervous system [88]. Increased gait variability, particularly in spatial and temporal gait, is considered a risk factor for falls in older people [90]. This imbalance between 'good' and 'bad' variability is different to younger adults, who typically show less variability overall and a ratio that more heavily favours the 'good' (functional) variability over the 'bad' [95]. From a clinical perspective, these findings may suggest a particular focus on maintaining consistent gait during dual-task situations when working with older adults, however, this recommendation should be considered on the premise that two types of variability exist. A meta-analysis by König, Singh, Baumann and Taylor [96] examined whether variability measures could, indeed, support clinical decision-making or the identification of clinical gait or pathological gait patterns. These authors

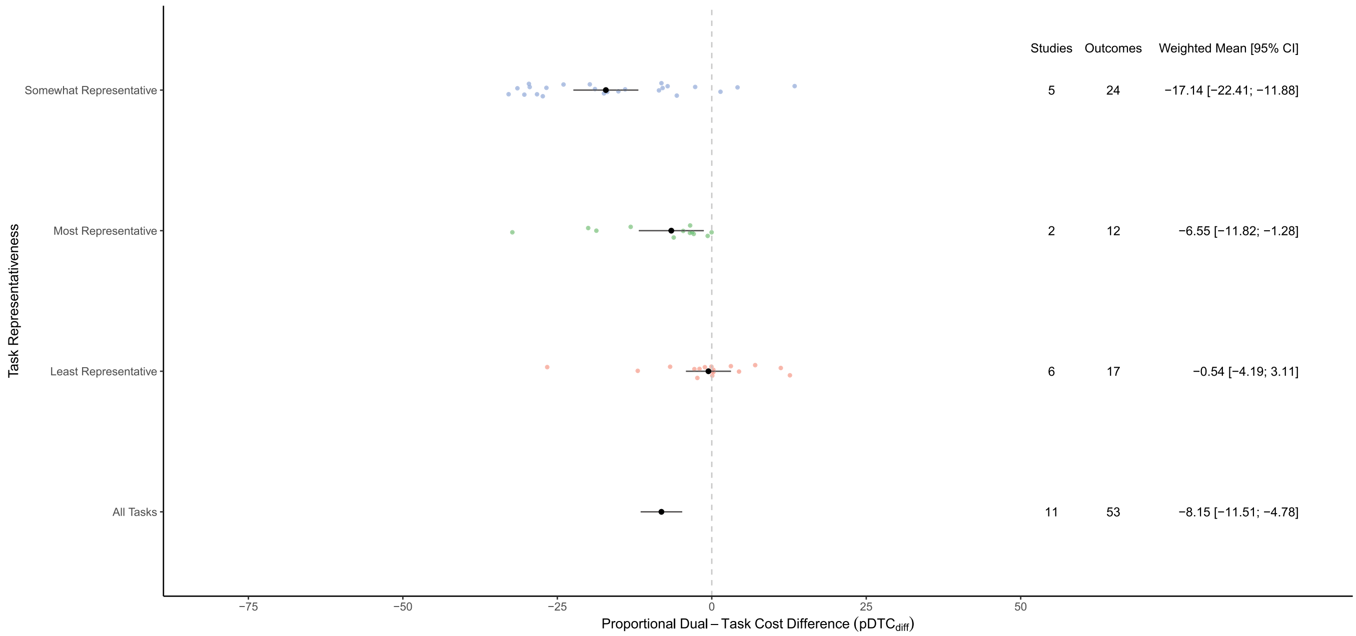

Fig. 7. Average cognitive $pDTC_{diff}$ results as a function of task representativeness.

provided cut-off scores that were based on the percentage difference required for certain variability measures to discriminate between healthy older adults and those with Parkinson's disease. These cut-off scores provide insight into the subtle distinction between 'functional' and 'non-functional' variability and support the notion that the goal of training should not be the outright reduction of all variability, but rather the reduction of non-functional variability.

When considering the choice of cognitive task during dual-task training, pooled results for such a task (see Fig. 4) may provide some guidance in scaling its difficulty. Tasks that result in smaller pDTCs (e.g., sustained attention/vigilance) may be beneficial early in training, whereas tasks that result in larger pDTCs (e.g., arithmetic tasks and texting) may be useful to further challenge participants. The above findings can be used to guide the choice of cognitive tasks in future dual-task research. To produce the greatest dual-task interference on gait outcomes, arithmetic, Stroop, and texting tasks appear more likely to elicit differences between older and younger adults. This is consistent with past findings that found older adults experienced the greatest change to gait speed and variability when simultaneously completing a mental tracking task and arithmetic task, respectively [26,97]. These results also align with theoretical accounts such as the HAROLD model, which suggests that older adults tend to recruit additional (and bilateral) brain regions when performing motor and cognitive tasks to compensate for age-related decline in the sensorimotor system [22]. This has broader implications for task performance as older adults tend to engage in inefficient cognitive processing when compared to younger adults [21]. For example, older adults show a more bilateral prefrontal activation when presented with a memory task, while younger adults show a more unilateral activation [98]. The large interference observed for the texting tasks is also consistent with the prediction that a visually demanding cognitive task will impact older adults exponentially [28].

Our findings (esp. see Fig. 4) also highlight the variation in group effects that are shown within and across cognitive task paradigms. Mental tracking and working memory type tasks (e.g., arithmetic, serial subtractions, recall memory tasks) that rely heavily on attention and one's capacity to mentally manipulate or transform information. Despite this commonality, not all tasks within this cognitive paradigm produced significant differences in motor pDTCs between younger and older adults. For example, arithmetic tasks produced a notably larger pDTC difference than the serial subtractions 7 tasks. It has been noted in recent studies that serial subtraction ability shows high levels of individual variation [99]. This fact and our results raise concerns about its construct validity and its useability in comparison-based studies. This individual variation may be largely because as a single task, serial subtractions is not an activity that is routinely performed in day-to-day life. Our interactions with our environment are often more complex and require a deeper level of cognitive processing (e.g., walking while reading and interpreting a sign ahead) [2]. Further, a recent review reported that the training effects found in dual-task intervention studies did not transfer to real-world scenarios [8].

When tasks were categorised according to their level of representativeness, both younger and older adults showed higher motor costs when the cognitive task was more representative of 'real-world' activities (see Fig. 5). The 'most representative' tasks also elicited stronger age effects with older adults showing greater costs to their motor performance than younger adults. These findings appear to mirror those behaviours that older adults adopt in the real world to compensate for age-related changes in dual-task performance. For example, older adults are known to slow their gait [100] or take shorter steps [101] in dual-task situations to preserve their safety. Further, these results also have important clinical implications as they provide a data-driven prediction about the difference in proportional cost (17 %) between younger and older adults for dual-tasks performed in a real-world setting. Taken together, we recommended that future studies employ dual-task protocols that are more representative of everyday behaviour to obtain a more (ecologically) valid understanding of age-related declines and/or compensations in dual-task performance [32].

Only around one-third of studies reported pDTC on cognitive measures, with only 53 individual outcomes included in the analysis. It is recommended that studies report both motor and cognitive single- and dual-task results, particularly given that cognitive outcomes are often easily recorded. Apart from the texting and auditory processing tasks, there was substantial variation in the number of studies and outcomes presented for each cognitive task. When all outcomes and studies were combined, older adults showed larger cognitive DTCs than younger. Specifically, there was a large and significant difference when both groups were required to walk and text. Notably, this task also produced a large group effect on motor pDTCs. It is possible that when the cognitive task was texting, older adults inadvertently gave equal priority to both tasks, contrary to the 'posture-first' strategy that is often employed by older adults, where gait stability is prioritised over cognitive tasks [102]. A possible explanation for this opposing finding is that these dual-task paradigms had a more substantial motor aspect than most cognitive tasks. For example, two out of four studies required participants to transcribe auditory information to text, a process that relies heavily on a participant's ability to carry out a manual task and fine motor task (i.e., holding phone and typing on the keypad), while also completing a motor (i.e., walking) and cognitive task (i.e., retaining information). Older adults also had larger pDTCs than younger adults while walking and completing an auditory processing task that assesses reaction time to sound stimuli. This process has important real-life safety implications, as slow reaction times can pose a risk in situations where warning messages are being conveyed via auditory means. This finding may reflect a posture-first strategy, whereby older adults prioritised their walking over cognitive performance. This hypothesis is supported by the review of Al-Yahya et al. [26] who concluded that older adults experienced the least dual-task interference on their motor performance when completing reaction time tasks. Notably, it is also possible that the included studies did not control for sensory impairments or deficits, such as poor hearing. We know from earlier studies that older adults with severe hearing loss show greater motor dual-task costs [103] and worse cognitive performance than participants with unimpaired hearing [104]. Future studies should screen for sensory impairments when recruiting participants or include this factor as a moderator in all analyses.

Recent reviews suggest that pDTC metrics be chosen with careful reference to reported validity and reliability data. If pDTC outcomes are not related to clinical measures (i.e., construct validity) or do not produce consistent outcomes over repeated measurements (i.e., test-retest reliability), they are likely to have little value, and may even produce misleading conclusions. While dual-task protocols generally demonstrate acceptable reliability and validity [43,105,106], a meta-analysis of the psychometric properties of DTC metrics has shown that motor DTC metrics generally have acceptable test-retest reliability in older adults but vary as a function of the specific gait metric [44]. Further, although data were not available for older adults, reliability of cognitive DTC and concurrent validity of both motor and cognitive DTC outcomes was poor for younger adults and clinical groups, such as those with multiple sclerosis, acquired brain injury, Parkinson's disease, and dementia. To be confident in the use of dual-task protocols, clinicians and researchers should ensure that the specific protocols and outcome measures are adequately validated prior to their use.

5. Study limitations

Many dual-task studies do not report pDTC outcomes, instead favouring absolute DTC. To capture a wide range of locomotor-cognitive dual-task research in our analysis of pDTCs, all studies that reported single- and dual-task outcome measures were included in the analysis. From these data, pDTCs were calculated for each age group and each outcome measure. However, as measures of outcome variance could not be calculated from the available data, pDTC outcomes were combined using weighted means instead of more traditional meta-analysis methods (e.g., effect size calculation and random-effects meta-analysis). Between study heterogeneity was assessed using Levene's tests. This approach enabled a large number of pDTC outcomes to be synthesised, providing a valuable summary of the available literature. To allow future synthesis of results using traditional meta-analyses procedures, researchers are encouraged to report pDTC outcomes, using standard formulae, along with single- and dual-task results.

6. Conclusion

Proportional DTC metrics quantify the relative influence of performing a second task relative to the performance of a single task. The current findings suggest that older adults' motor performance is more heavily impacted by the performance of a cognitive task than younger adults, but that the magnitude of interference varies depending on the specific motor outcome and cognitive task that is assessed. It is recommended that future research use more representative cognitive tasks, as laboratory-based tasks may not be highlighting the dual-task costs that certain populations experience in the real world. Insights such as these can make valuable contributions to the development of dual-task training programs for the ageing population.

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CRediT authorship contribution statement

Wilson Peter H: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Cole Michael H:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **McGuckian Thomas B:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mustafovska Jona:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors report no conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.04.012.

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