Experimental Brain Research (2022) 240:703–731
https://doi.org/10.1007/s00221-021-06299-y

REVIEW

Effect of cognitive task complexity on dual task postural stability: a systematic review and meta-analysis

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Received: 24 September 2021 / Accepted: 21 December 2021 / Published online: 16 January 2022

Abstract
The dual task experimental paradigm is used to probe the attentional requirements of postural control. However, findings of dual task postural studies have been inconsistent with many studies even reporting improvement in postural stability during dual tasking and thus raising questions about cognitive involvement in postural control. A U-shaped non-linear relationship has been hypothesized between cognitive task complexity and dual task postural stability suggesting that the inconsistent results might have arisen from the use of cognitive tasks of varying complexities. To systematically review experimental studies that compared the effect of simple and complex cognitive tasks on postural stability during dual tasking, we searched seven electronic databases for relevant studies published between 1980 to September 2020. 33 studies involving a total of 1068 participants met the review's inclusion criteria, 17 of which were included in meta-analysis (healthy young adults: 15 studies, 281 participants; Stroke patients: 2 studies, 52 participants). Narrative synthesis of the findings in studies involving healthy old adults was carried out. Our result suggests that in healthy population, cognitive task complexity may not determine whether postural stability increases or decreases during dual tasking (effect of cognitive task complexity was not statistically significant; $P > 0.1$), and thus the U-shaped non-linear hypothesis is not supported. Rather, differential effect of dual tasking on postural stability was observed mainly based on the age of the participants and postural task challenge, implying that the involvement of cognitive resources or higher cortical functions in the control of postural stability may largely depends on these two factors.

Keywords Cognitive task complexity · Dual tasking · Postural stability · Postural control

Introduction

Effective postural stability is essential for the performance of routine activities under both static and dynamic conditions (Haddad et al. 2013). The involvement of both automatic and cognitively controlled processes in the control of postural stability is well reported in the literature (Boisgontier et al. 2013, 2017; Takakusaki 2017). Several lines of evidence indicate that the process of postural control can be automatically regulated by neural circuits located in the cerebellum, brain stem and spinal cord (Boisgontier et al. 2017; Drijkoningen et al. 2015; Magnus 1926; Morton and Bastian 2004). Multi-sensory information from the visual, vestibular, and proprioceptive systems is integrated in these neuronal networks to achieve stable posture (Takakusaki 2017). Other research, however, suggests that the process regulating the postural adjustments necessary for maintaining stability is attention-demanding and thus requires higher-order cognitive processing (Boisgontier et al. 2013; Fraizer and Mitra 2008; Jacobs and Horak 2007; Kerr et al. 1985; Woollacott and Shumway-Cook 2002). Indeed, even the highly practiced postural task of maintaining upright stance has been shown to require some degree of attention (Marsh and Geel 2000; Vuillerme et al. 2006). Other more challenging static postural tasks such as standing upright with eyes closed (Romberg stance), placing one foot in front of the

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Communicated by Bill J. Yates.

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other (Tandem stance), single leg stance and the control of postural stability during gait have likewise been shown to be attention-demanding (Hwang et al. 2013; Lajoie et al. 1993; Teasdale et al. 1993).

Consequently, it is expected that performing a cognitive task concurrently with a postural task would decrease the amount of available attentional resources for postural control, which may lead to a reduction in postural stability (Andrade et al. 2014; Brown et al. 1999; M Lanzarin et al. 2015a, b). This is based on the cross-domain resource competition hypothesis which postulates that both maintenance of postural stability and cognitive task performance draw from a limited pool of cognitive resources for their control, potentially leading to a decrease in postural stability, cognitive task performance, or both, when the two tasks are carried out simultaneously (Kahneman 1973; Tombu and Jolicoeur, 2003; Wickens et al. 1983; Wollesen et al. 2016). Moreover, when the cognitive task performed is complex, it may use larger amounts of attentional resources thereby leaving postural stability more under resourced particularly in older adults (Bernard-Demanze et al. 2009; Boisgontier et al. 2013; Ruffieux et al. 2015). The dual task paradigm has been used to probe the cognitive demand of postural control by investigating how postural stability will be impacted when a postural task is carried out alongside a cognitive task in numerous studies in both healthy young and older adults and in patients with neurological conditions.

However, contradictory, often diametrically opposed results were reported in dual task posture studies involving both healthy and clinical populations, thereby raising questions about cognitive involvement in postural control (Stins and Beek 2012). While some studies found a decrease in postural stability during dual tasking as expected (Andersson et al. 1998; Andrade et al. 2014; Bensoussan et al. 2007; Brown et al. 1999; Doumas et al. 2008; Jacobi et al. 2015; M Lanzarin et al. 2015a, b; Maki and McIlroy 1996; Marchese et al. 2003; Melzer et al. 2001; Morris et al. 2000; Plummer et al. 2013; Prosperini et al. 2015; Ramenzoni et al. 2007; Redfern et al. 2004; Shumway-Cook and Woollacott 2000; Simoneau et al. 1999; Stelmach et al. 1990), others reported no change (Brown et al. 1999; Doumas et al. 2008; Marsh and Geel 2000; Shumway-Cook and Woollacott 2000; Stelmach et al. 1990; Swan et al. 2004; Nicolas Vuillerme and Vincent 2006) and some even reported an improvement in postural stability (Andersson et al. 2002; Bergamin et al. 2014; Donker et al. 2007; Hunter and Hoffman 2001; Hwang et al. 2013; Hyndman et al. 2006; Maylor et al. 2001; Negahban et al. 2011; Plummer et al. 2013; Resch et al. 2011; Richer et al. 2017a, b; Swan et al. 2004). Overall, in a systematic review on the effects of dual tasking on postural stability, Ghai and colleagues reported that only 50% of the included studies found a decrease in postural stability during dual tasking. The remaining 20% and 30% found no effect and improvement in postural stability, respectively (Ghai et al. 2017). Similar inconsistent effects of dual tasking on postural stability were also reported in two earlier systematic reviews (Boisgontier et al. 2013; Fraizer and Mitra 2008).

It has been suggested that the inconsistencies in the literature on the effect of dual tasking on postural stability could have resulted from the use of cognitive tasks with varying complexities as well as differing balance tasks (Andersson et al. 2002). In the context of dual tasking, when postural demand on attentional resources is low, a similarly low attention demanding cognitive task may not adversely affect postural stability, but a more demanding task may (Shumway-Cook et al. 1997). However, when postural demands are high, even a relatively simple cognitive task might negatively affect postural stability. In another view, postural stability during dual tasking would either improve or deteriorate depending on whether the cognitive demand of the secondary task (i.e., the cognitive task) is low or high (Huxhold et al. 2006). A simple cognitive task might improve postural stability by serving as an external focus of attention (Wulf et al. 2001), but when a more complex cognitive task is used, attentional resource competition between cognitive and sensorimotor processing would ensue, potentially leading to reduction of postural stability (U-shaped non-linear hypothesis) (Huxhold et al. 2006).

Several studies have been conducted directly comparing the effects of simple and more complex cognitive tasks on postural stability during dual tasking in different populations (Bernard-Demanze et al. 2009; Boisgontier et al. 2013; Mehdizadeh et al. 2018; Pellecchia 2003), however, to date, the findings of these studies have not been synthesized and summarized in a systematic review and meta-analysis. The meta-analysis by Ghai and colleagues which suggests differential effect of cognitive task complexity, was not based on studies that directly compared simple and complex cognitive tasks. In fact, the aim of their review was not primarily to investigate the effect of cognitive task complexity on dual task postural stability, and thus their literature search and inclusion criteria might not target relevant studies. Additionally, their analysis was confined to data from only six studies (two in multiple sclerosis patients, two in healthy young adults and another two in older adults) (Boes et al. 2012; Holmes et al. 2010; Morgan Lanzarin et al. 2015a, b; Melzer et al. 2001; Negahban et al. 2011; Resch et al. 2011) and apparently the studies used different types of cognitive tasks and different cognitive response modality (verbal or non-verbal) not different complexities. Upon analysis, the summary effect from the two studies pooled in both the healthy young adults and multiple sclerosis patients were non-significant. However, because their reported effect size is in the negative domain and considerable heterogeneity was observed among the included studies, the authors suggested that this may have been due a differential effect of cognitive task complexity.

Essentially, the review by Ghai and colleagues cannot be said to have demonstrated differential effects of cognitive task complexity based on their methodology and statistical analysis. A carefully designed systematic review and meta-analysis with properly defined inclusion criteria and appropriate statistical analysis is therefore needed to assess the effect of cognitive task complexity on postural stability during dual tasking.

The primary aim of this study is to systematically review the findings of the studies that directly compare the effect of simple and complex cognitive tasks on postural stability in standing during dual tasking and examine whether simple cognitive tasks affect postural stability differently compared to complex cognitive tasks.

Methods

The review was conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) guidelines (Moher et al. 2009).

Data sources and search strategy

Electronic databases including Ovid Medline, EMBASE, Cochrane CENTRAL, Scopus, Pubmed, CINAHL Plus and PsycINFO were searched from 1980 until September 2020. The search terms used were standing OR posture OR balance AND attentional demands OR attentional load OR cognitive load OR complex cognitive task OR dual task OR task difficulty OR concurrent task OR secondary task OR task complexity NOT training or exercise. These were modified in terms of the glossary of each database and were truncated and mapped to medical subject heading (MeSH) terms where appropriate. An example of the search strategy for EMBASE database has been provided (Table 1). Moreover, studies obtained from the general literature search were added. Results were then exported to Endnote X9 (Clarivate analytics, Philadelphia) where duplicates were removed and later exported to covidence (www.covidence.org) for further screening.

Table 1 Sample search strategy for EMBASE database

1	posture/
2	posture.ab,kw,ti.
3	balance.ab,kw,ti.
4	standing.ab,kw,ti.
5	1 OR 2 OR 3 OR 4
6	dual task*.ab,kw,ti.
7	attentional demand.ab,kw,ti.
8	attentional load.ab,kw,ti.
9	cognitive load*.ab,kw,ti.
10	complex cognitive task.ab,kw,ti.
11	dual task difficulty.ab,kw,ti.
12	concurrent task.ab,kw,ti.
13	secondary task.ab,kw,ti.
14	task complexity.ab,kw,ti.
15	6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14
16	5 AND 15
17	exercise/
18	exercise.ab,kw,ti.
19	training.ab,kw,ti.
20	17 OR 18 OR 19
21	16 NOT 20

Study selection

After duplicates were removed, the remaining studies were independently screened by the first reviewer for eligibility. At the first stage, the titles and abstracts of the studies were screened and those deemed ineligible were excluded. Inclusion and exclusion criteria were then applied to the full text of the remaining studies. Studies were included if they: (1) involved human participants; (2) were written in English language and published in peer reviewed journals; (3) used dual task paradigm where the primary task was balance and the secondary task was a cognitive task. The studies where the primary task was a cognitive task may not report the effect of dual tasking on balance as their focus is primarily on the effect of dual tasking on cognitive performance.; (4) reported balance and cognitive performance under both single and dual task conditions (or the effect of dual tasking on both balance and cognitive performance) or at least reported balance measurement during both single and dual task performance (or the effect of dual tasking on balance); (5) compared different complexities of the secondary task (simple and complex cognitive tasks); (6) explicitly stated the simple and the complex cognitive tasks in the introduction or the method section; (7) used valid and reliable methods for assessment of balance. Dissertations, review articles and conference abstracts were excluded. Studies that analyzed postural stability in the sitting position only and those in children under 18 years were not included. This is because the sitting position often only serves as the baseline for cognitive assessment in dual-task experiments; and the development of postural control centres may not be complete in childhood and adolescence (Ghai et al. 2017; Lajoie et al. 1993; Steindl et al. 2006). Uncertainty about eligibility assessment was resolved by discussion and consensus among all the authors.

Quality assessment and data extraction

Because the included studies had a within-subjects (pre-post-test) design, traditional tools for quality assessment of randomized controlled trials are not suitable. For this reason, the methodological quality of the included studies was assessed using a customized 15 points checklist based on the tool developed by Downs and Black (Downs and Black 1998) (Supplementary material 1). This tool was previously used by systematic reviews of studies of this nature (Lee et al. 2013; Smith et al. 2016). Each paper was assigned a grade of "excellent" (14–15 points), "good" (11–13 points), "fair" (7–10 points) or "poor quality" (< 7 points) (Silverman et al. 2012). For each included study, the following data were extracted and tabulated: author and year of publication, study design, sample size, sample description (age, gender, health status), postural task, postural assessment tool, postural outcome measure, simple cognitive task, complex cognitive task, and the resulting effect on postural stability.

Data synthesis and analysis

Mean and standard deviations were used to calculate effect sizes. Where these descriptive data were not provided numerically, they were extracted from graphs, if available, using Plot digitizer software (Huwaldt 2005). This is a highly reliable Java-based software program that converts plotted values into numerical format (Kadic et al. 2016) and is widely used in meta-analytical studies (Bastani and Jaberzadeh 2012; Butler et al. 2013; Chung et al. 2016; Dissanayaka et al. 2017; Hill et al. 2016; Pisegna et al. 2016; Vaseghi et al. 2015). In situations where standard error (SE) was reported instead of standard deviation (SD), SD was estimated using the formula $\text{SD} = \text{SE} \times \sqrt{n}$ (n = number of subjects) (J. Higgins 2011). If neither graphical nor numerical data was provided in a study, the required information was requested from the corresponding author via email. Since the included studies have a within-subjects (pre-post-test) design rather than randomized control trials (RCT) design, pre-post correlation was set to 0.5 (Balk et al. 2013).

Except for sway variability, effect sizes were expressed as differences in means (MD), since the outcome measurements were made or could be converted on the same scale (Sway area-millimetre square, Sway velocity-millimetre per second, Total sway path length-millimetre and Sway frequency-Hertz). As the sway variability was measured on different scales in the included studies, effect sizes for this outcome measure were calculated as Cohen's d standardized difference (Rosenthal et al. 1994). Data for young adults and patients with pathological conditions were analyzed separately. In situations where studies used more than one outcome measure for assessment of postural stability, data from each outcome measure were separated in individual meta-analysis (Ilieva et al. 2015). Forest plots with 95% confidence intervals (CIs) are reported and standardized effect sizes (sway variability) were interpreted as small (˂0.1), medium (0.1–0.3) or large (˃ 0.3) (Cohen 1988; Ghai et al. 2017; J. P. Higgins 2008). Negative effect size indicates a decrease in postural stability while positive ones show improvement. Heterogeneity was quantified using the I^2 statistic, which can range from 0 to 100%, where 0–40% might not be important, 30–60% represents moderate heterogeneity, 50–90% represents substantial heterogeneity, and 75–100% represents considerable heterogeneity (Ryan 2016). To compare the effect of simple and complex cognitive tasks on dual task postural stability, a subgroup analysis was conducted (Al-Yahya et al. 2011). Subgroup analyses were conducted using a mixed-effects model whereby the summary effects within subgroups were computed using a random-effects model, while the differences across subgroups were assessed using a fixed-effects model (Al-Yahya et al. 2011; Borenstein et al. 2021). A p-value of less than 0.1 indicates a statistically significant subgroup effect (Richardson et al. 2019) whereas p values of ≤ 0.05 indicates significant effect of dual tasking within the subgroups. Result of the subgroup analysis was interpreted according to previous recommendations (Bloom and Michalopoulos 2013; Richardson et al. 2019). To accurately assess attentional costs associated with postural control, it is essential to have access to performance for both the postural and cognitive tasks in both single-task and dual-task conditions (i.e., 4 different conditions) (Boisgontier et al. 2013). However, it is common to find dual task postural studies that reported on only the postural performance (i.e., 2 different conditions) without the corresponding report of the change in cognitive performance between single and dual tasks. Therefore, in our first analysis, we included studies even if the change in cognitive performance between single and dual tasks was not reported. We then carried out a robustness analysis where we controlled for changes in cognitive performance by including only those studies that reported the effect of dual tasking on both postural and cognitive performance. Comprehensive Meta-Analysis software, version 3 was used for all analysis. Where meta-analysis cannot be conducted due to a lack of descriptive data (mean & SD), a narrative synthesis based on the findings of the included studies was provided.

Results

Studies and participants

A total of 268 articles were identified after duplicates were removed and titles and abstracts were screened from the initial search result (Fig. 1). After applying the eligibility criteria, 235 articles were removed leaving 33 articles which

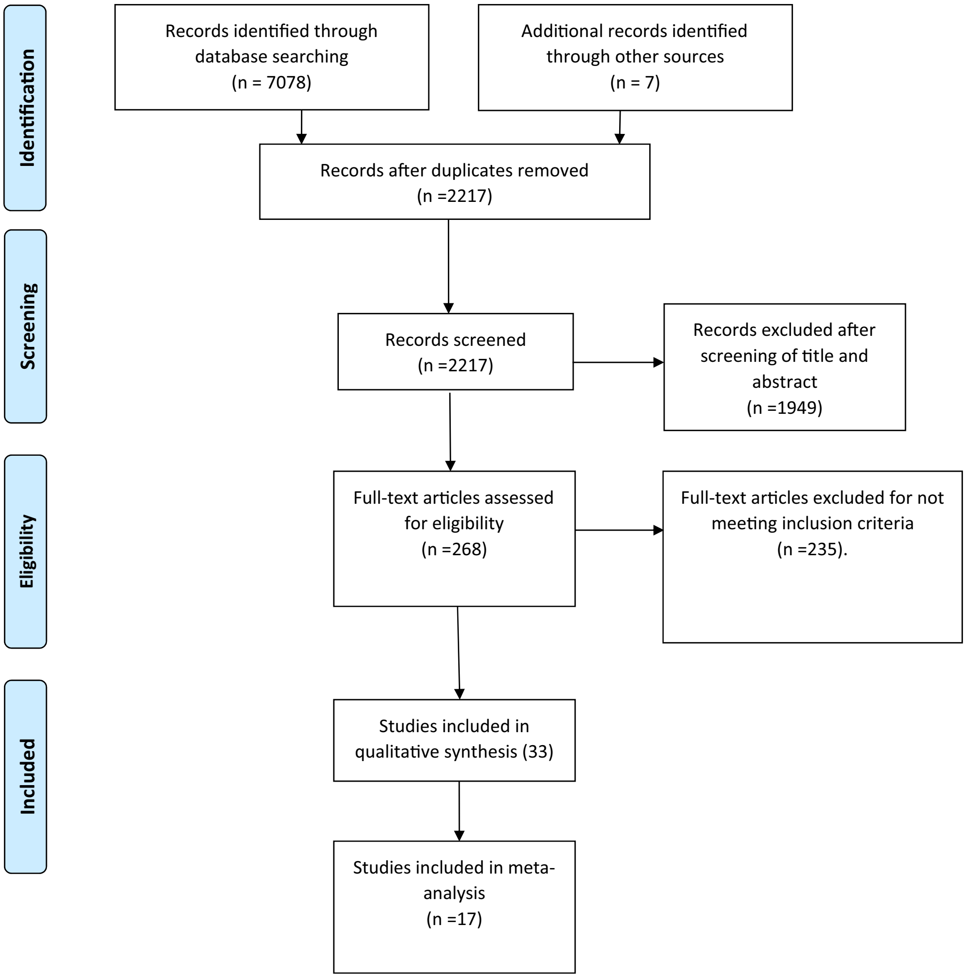


Fig. 1 Flow diagram showing selection process of articles following PRISMA guidelines

were finally included in the study. All included studies had a within-subject design including both single and dual-task postural stability testing, paired with simple and complex cognitive tasks. Nine studies included participants with various pathological conditions such as stroke, Parkinson's disease, traumatic brain injury and cognitive impairment. Three studies (Bernard-Demanze et al. 2009; Bohle et al. 2019; Huxhold et al. 2006) included both healthy young and older adults while 20 studies included only healthy young adults. The remaining study included only healthy older adults (Lajoie et al. 2017).

Mixed-gender participant groups were incorporated by 27 studies, whereas two studies (Swan et al. 2007; Vuillerme et al. 2000) included only female participants. In one study (Oliaei et al. 2018), only male participants were included and the remaining three studies (Bourlon et al. 2014; Dault et al. 2003; Vuillerme and Vincent 2006) did not provide information about the gender distribution of the participants. The total number of participants in the included studies is 1068 (median of 20 participants/study). Most of the studies (26 studies) provided the mean age of the participants, five studies provided the age range of their participants, while two studies did not provide the range nor mean age of their participants. The characteristics of the studies and the participants are summarized and tabulated (Table 2). The observed effects of both simple and complex cognitive tasks on dual-task postural stability based on the analysis of statistical significance in each study are also presented in the same table. Because of inclusion of more than one group of participants (e.g., patients and control, old and young) and more than one type of cognitive task, each with its simple and complex variants, in some studies, a total of 52 data sets were presented from the 33 included studies (Table 2).

Characteristics of the cognitive and postural tasks

Based on the classification of cognitive tasks by Al-Yahya (Al-Yahya et al. 2011), different types of tasks including mental tracking, working memory, discrimination and decision making, reaction time and verbal fluency tasks were used in the various studies. Moreover, in most of the studies (26 studies), cognitive task complexity was manipulated within the same type of task, while seven studies used

Table 2 The effect of cognitive task complexity on dual task postural stability in healthy young adults, older adults and in patients with pathological conditions

Study	Design	Sample size	Age (Years)	Gender		Balance			Cognitive task		Effect on balance	
				Male	Female	Assessment task	Assessment tool	Outcome measure	Simple	Complex	Simple	Complex
The effect of cognitive task complexity on dual task postural stability in healthy young adults												
Bernard-Demanze et al 2009	Within-subject design	8	28.0	3	5	Standing Standing with platform translation (Dynamic balance)	Force plate	Postural sway, Postural instability index, Energy and time for body re-stabilization	Mental arithmetic task (addition and subtraction based on single digits from 1±1 to 9±9 selected randomly)	Spatial memory task (multi-step translation on a 3x3 cell grid)	↑ postural stability	↑ postural stability (*)
Bustillo-casero et al 2017	Within-subject design	15	21.22	7	8	bipedal stance tandem stance unipedal stance	Wii Balance Board (WWB), with four strain gauge load sensors	Postural sway	backward digit span test 3-Digit sequences	backward digit span test 5-Digit sequences	—	—
Bohle et al 2019	within-subject block design	28	25	15	13	Standing in a semi-tandem stance on a balance pad (unstable surface)	Force plate	Postural sway	visual or auditory 1-back task	Combined visual and auditory 1-back task	—	—
Bourlon et al 2014	Within-subject design	12	49.0	-	-	Standing	Force plate	Postural sway	Simple RT task	Complex RT task	—	—
Barra et al 2006 (Spatial task)	Within-subject design	16	34.4	9	7	Standing in Romberg position on beam (easy, Medium or hard)	Force plate Hip gyroscope	Postural sway Number of falls	Spatial stroop (t=2.5s)	Spatial stroop (t=1.5s)	↓ (medium and hard beam)	↓ (medium and hard beam)
Barra et al 2006 (Verbal task)	Within-subject design	16	35.6	8	8	Standing in Romberg position on beam (easy, Medium or hard)	Force plate Hip gyroscope	Postural sway Number of falls	Verbal stroop(t=2.5s)	Verbal stroop(t=1.5s)	↑ postural stability	↑ postural stability
Brauer et al 2004 (non-spatial task)	Within-subject design	20	-	13	7	Standing in a step stance position	Force plate	Postural sway	non-spatial task (signal detection task)	non-spatial task (controlled oral word association test [COWAT])	—	↓ postural stability
Brauer et al 2004 (spatial task)	Within-subject design	20	-	13	7	Standing in a step stance position	Force plate	Postural sway	Visuo-spatial task (comparing series of two spatial patterns)	visuo-spatial task (Judgement of line orientation test [JOLO])	—	—
Dault et al 2001$_b$	Within-subjects design	24	20-40	12	12	Shoulder width stance Shoulder width stance on see-saw Tandem stance on see-saw	Force plate	Postural sway	stroop task (word card)	stroop task (colour-word card)	↓ postural stability (tandem see-saw) ↑ postural stability (shoulder see-saw	↓ postural stability (tandem see-saw) ↑ postural stability (shoulder see-saw
Dault et al 2003 (combination task)	Within-subjects design	20	29.8	-	-	Standing on stable surface (EO, EC) Standing on unstable surface (EO, EC)	Force plate	Postural sway	articulation task (asking participants to repeat letters aloud without having to form any words)	combination task (participants had to repeat each letter aloud immediately after hearing it, as well as form the words and say the	↓ postural stability	↓ postural stability

different types of tasks to represent simple and complex cognitive tasks (Table 2).

Different postural tasks were also used across the studies. In seven studies, standing with feet shoulder-width apart and eyes opened (standing or quiet standing) was used as the postural task, while 12 studies used other more challenging postural tasks such standing with eyes closed, standing on a see-saw, standing on a piece of foam, or single leg stance, in addition to quiet standing. Fourteen studies used only challenging postural tasks (Table 2).

Table 2 (continued)

										phrase aloud at the end)		
Dault et al 2003 (Silent task)	Within-subjects design	20	29.8	-	-	Standing on stable surface (EO, EC) Standing on unstable surface (EO, EC)	Force plate	Postural sway	articulation task (asking participants to repeat letters aloud without having to form any words)	Silent task (Similar to combination task but no articulation is required	↓ postural stability	↑ postural stability
Hauer et al 2003	Within-subject design	20	25.4	4	16	Standing	Balance Performance Monitor	Postural sway	Serial-2 addition	Serial-7 subtraction	—	—
Linder et al 2019	Within-subject design	50	18–24	25	25	Double leg stance (EO, EC) Tandem stance (EO, EC)	Accelerometer and gyroscope	Cleveland Clinic-Postural Stability Index	Number discrimination task (30 stimuli/min)	Number discrimination task (90 stimuli/min)	—	—
Salvati et al 2009	Within-subject design	22	25.0	13	9	Standing on rigid surface (EO, EC) Standing on foam surface (EC)	Force plate	Postural sway	Backward digit span task (half of the digits of the difficult task)	Backward digit span task (maximum number of digits recalled at baseline plus one)	—	↑ postural stability
Mujdeci et al 2015	Within-subject design	20	22.40	10	10	Sensory organisation test (c1-c6)	Neuro-Com Smart Balance Master	Sensory organisation test score	digit memory test (half of the maximum number of digits recalled)	digit memory test (maximum number of digits recalled)	↓ postural stability (c1-c4)	↓ postural stability (c1-c4)
Olivier et al 2010	Within-subject design	9	25.7	7	2	Semitandem stance (with or without ankle vibration)	Force plate	Postural sway	Modified colour-word stroop task (Congruent)	Modified colour-word stroop task (Non-congruent)	—	—
Onofrei et al 2020	Within-subject design	35	21.37	13	22	Standing	Podoscope	Postural sway	Talking on smart phone	Texting on smart phone	↓ postural stability (*)	↓ postural stability
Pellecchia 2003	Within-subject design	20	18-30	10	10	Standing on foam surface	Force plate	Postural sway	Digit reversal task (pair of digits-0 bit of information)	counting backward by 3s task (5.9bit reduction)	—	↓ postural stability
Rebold et al 2017	Within-subject design	45	20.03	16	29	Standing on Biodex Balance System (level 6)	Biodex Balance System	postural stability index score	Listening to music	Texting or talking on phone	—	↓ postural stability
Riley et al 2003	Within-subject design	23	Nil	10	13	Standing on foam surface with feet together	Force plate	Postural sway	digit memory test (half of the maximum number of digits recalled)	digit memory test (maximum number of digits recalled)	—	—
Riley et al 2005$_a$	Within-subject design	20	19.45	9	11	Standing with feet together on rigid surface (EO, EC) Standing with feet together on foam surface (EO, EC)	Force plate	Postural sway Recurrent quantification analysis	digit memory test (half of the maximum number of digits recalled) - VISUAL	digit memory test (maximum number of digits recalled)- VISUAL	—	↑ postural stability
Riley et al 2005$_b$	Within-subject design	20	21.9	6	14	Standing with feet together on rigid surface (EO, EC) Standing with feet together on foam surface (EO, EC)	Force plate	Postural sway Recurrent quantification analysis	digit memory test (half of the maximum number of digits recalled) - AUDITORY	digit memory test (half of the maximum number of digits recalled) - AUDITORY	—	↑ postural stability
Rougier and Bonnet 2016 (Mental calculation task)	Within-subject design	11	21–26	6	5	Standing with eyes closed	Force plate	Postural sway	Mental calculation task (at 130% of shortest time to complete the task)	Mental calculation task (shortest time to complete task)	—	—

Quality assessment

Methodological quality assessment scores obtained by individual studies are reported in Supplementary material 2. The average score for the 33 included studies was 10.9 out of 15 points using the customized assessment checklist based on that developed by Downs and Black, indicating overall fair quality of the included studies. Thirteen studies scored 11, eleven studies scored 10, four studies scored 13, three studies scored 12 and the remaining two studies scored 9. Common weaknesses observed included not reporting the actual probability values and the inability to determine whether the individuals asked to participate and those eventually recruited were representative of their entire

Table 2 (continued)

Rougier and Bonnet 2016 (Mental navigation task)	Within-subject design	11	21–26	6	5	Standing with eyes closed	Force plate	Postural sway	Mental navigation task (at 130% of shortest task completion time)	Mental navigation task (shortest time to complete the task)	—	—
Swan et al 2007	Within-subject design	98	18–27	0	98	Standing with feet together (with and without vibration to the bilateral gastrosnemius) Tandem stance All with eyes closed	Force plate	Proportion of time spent in balance correction	Brook's spatial and nonsense task (easy)	Brook's spatial and nonsense task (difficult)	—	↑ postural stability
Vuillerme et al 2000	Within-subject design	6	23.7	0	6	Standing	Force plate	Postural sway	Simple RT task (RT)	Complex RT task	↑ postural stability	↑ postural stability
Vuillerme and Vincent 2006	Within-subject design	13	21.0	-	-	Standing with eyes closed	Force plate	Postural sway	Mental arithmetic (additions and subtractions of series of single digits numbers every 4s)	Mental arithmetic (additions and subtractions of series of single digits numbers every 2s)	—	↑ postural stability
Yardley et al 2001 (Spatial task)	Within-subject design	24	44.25	11	13	standing with eyes closed on a stable platform standing with eyes closed on a destabilised, "sway referenced" platform.	EquiTest system.	Equilibrium score Postural sway	Spatial auditory discrimination tasks	Spatial categorisation of a numerical stimulus.	—	—
Yardley et al 2001 (non-spatial task)	Within-subject design	24	44.25	11	13	standing with eyes closed on a stable platform standing with eyes closed on a destabilised, "sway referenced" platform.	EquiTest system.	Equilibrium score Postural sway	Non-spatial auditory discrimination tasks	Non-spatial categorisation of a numerical stimulus	—	—
Dault et al 2001$_a$	Within-subject design	20	23	11	9	standing in shoulder width stance standing in tandem stance	Force plate	Postural sway	Visuo-spatial WM Task (easy)	Visuo-spatial WM Task (difficult)	↑ postural stability	↑ postural stability
Richer et al 2017	Within-subject design	25	20.7	10	15	Standing with feet together	Force plate	Postural sway	Counting the number of single digits in a sequence	Counting the number of double digits in a sequence	↓postural stability	↓postural stability
Zhang et al 2019	Within-subject design	14	25.9	6	8	Standing (EO, EC) with induced perturbation using ball-hitting test	Force plate	Postural sway	Serial 3-subtraction	Time-limited Serial 3-subtraction	↑ postural stability (EC, CPA)	↑ postural stability (EC, CPA)
Oliaei et al 2018	Within-subject design	8	27.8	8	0	Standing on an unstable platform (EO, EC)	2-D motion analysis	Postural sway	Simple question (e.g. five girls names starting with letter 'm' in the native Farsi language)	difficult question (e.g. five Iranian cities ending in letter 'a' or five three-letter Iranian cities)	—	—
Huxhold et al 2006	Within-subject design	20	24.52	10	10	Standing	Force plate	Postural sway	Simple perceptual task (watching a random series of digits ranging from one to nine)	digit 2-back working memory task.	↑ postural stability	↑ postural stability

population. Additionally, information on possible confounders and adjustments for them in the analysis was not reported and conducted in most of the studies.

Meta-analyses

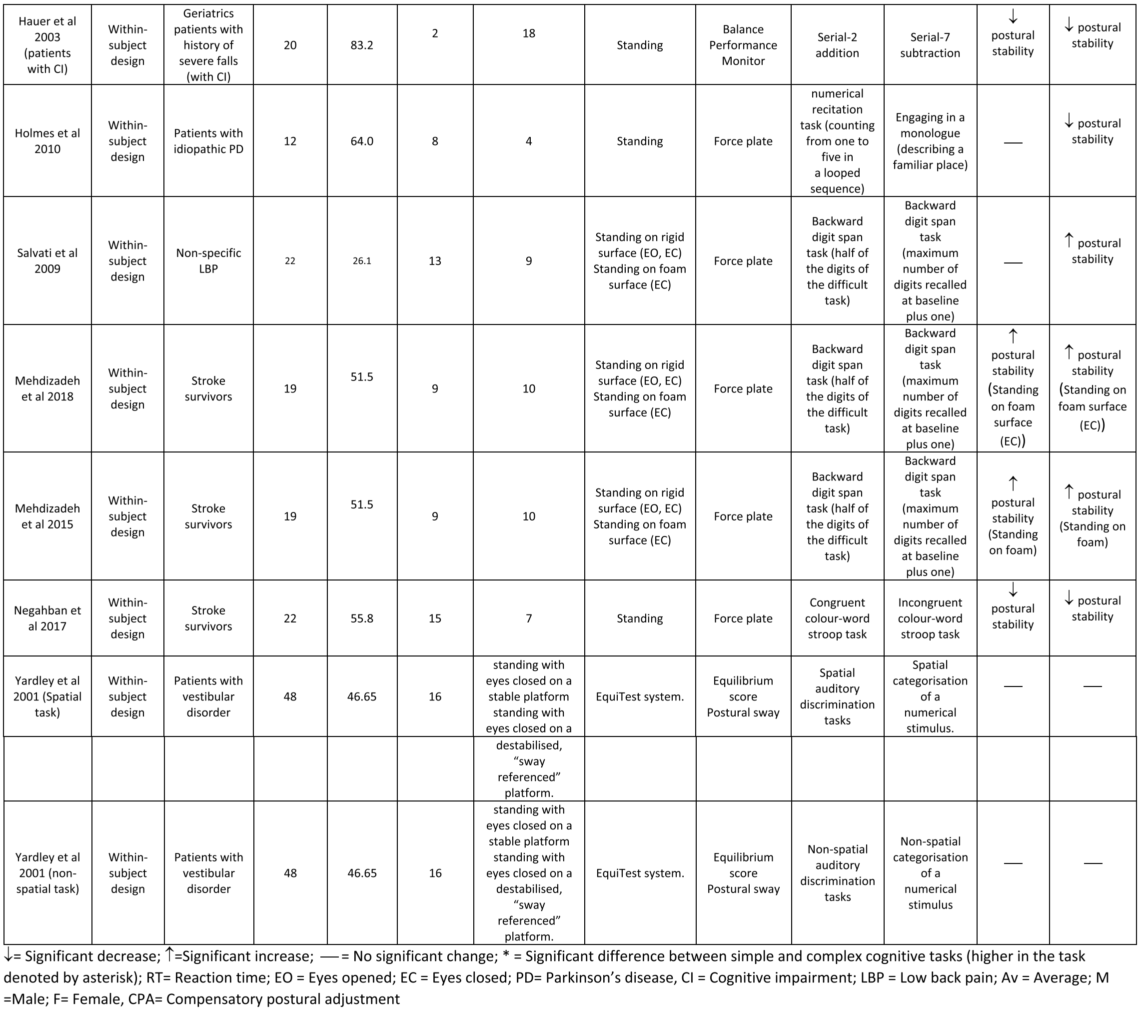
A total of 17 studies were included in the meta-analysis (Bohle et al. 2019; Bourlon et al. 2014; Brauer et al. 2004; Bustillo-Casero et al. 2017; Dault et al. 2001a, b; Dault et al. 2003; Hauer et al. 2003; Huxhold et al. 2006; Negahban et al. 2017; Olivier et al. 2010; Pellecchia 2003; Richer et al.

Table 2 (continued)

The effect of cognitive task complexity on dual task postural stability in healthy older adults												
Bernard-Demanze et al 2009 (Quiet standing)	Within-subject design	12	75.6	5	7	Standing	Force plate	Postural sway, Postural instability index,	Mental arithmetic task (addition and subtraction based on single digits from 1±1 to 9±9 selected randomly)	Spatial memory task (multi-step translation on a 3x3 cell grid)	↓ postural stability	↓ postural stability (*)
Bernard-Demanze et al 2009 (Dynamic platform)	Within-subject design	12	75.6	5	7	Standing	Force plate	Energy and time for body re-stabilization, gain, phase, spectral power density	Mental arithmetic task (addition and subtraction based on single digits from 1±1 to 9±9 selected randomly)	Spatial memory task (multi-step translation on a 3x3 cell grid)	↓ postural stability	↓ postural stability (*)
Bohle et al 2019	within-subject block design	30	71.7	17	13	Standing in a semi-tandem stance on a balance pad (Unstable surface)	Force plate	Postural sway	visual or auditory 1-back task	Combined visual and auditory 1-back task	↓ postural stability	↓ postural stability
Holmes et al 2010	Within-subject design	12	62.67	8	4	Standing	Force plate	Postural sway	numerical recitation task (counting from one to five in a looped sequence)	Engaging in a monologue (describing a familiar place)	—	↓ postural stability
Lajoie et al 2017 (Discrete task)	Within-subject design	20	69.9	4	16	Standing with feet together	Force plate	Postural sway	simple reaction time task	go/no go reaction time task	—	↑ postural stability
Lajoie et al 2017 (continuous task)	Within-subject design	20	69.9	4	16	Standing with feet together	Force plate	Postural sway	equation task	sequence task	↓ postural stability	↓ postural stability (*)
Huxhold et al 2006	Within-subject design	19	69.80	10	90	Standing	Force plate	Postural sway	Simple perceptual task (watching a random series of digits ranging from one to nine)	digit 2-back working memory task.	↑ postural stability	↓ postural stability
Study	Design	population	Sample size	Age (Years)	Gender		Balance		Cognitive task		Effect on balance	
					Male	Female	Assessment task	Assessment tool	Simple	Complex	Simple	Complex
The effect of cognitive task complexity on dual task postural stability in patients with pathological conditions												
Bourlon et al 2014	Within-subject design	Right hemispheric stroke	30	54.3	19	11	Standing	Force plate	Simple RT task	Complex RT task	—	↑ postural stability
Brauer et al 2004 (non-spatial task)	Within-subject design	young adults with severe brain injury	20	32.9	13	7	Standing in a step stance position	Force plate	non-spatial task (signal detection task)	non-spatial task (controlled oral word association test [COWAT])	↓ postural stability	↓ postural stability
Brauer et al 2004 (spatial task)	Within-subject design	young adults with severe brain injury	20	32.9	13	7	Standing in a step stance position	Force plate	Visuo-spatial task (comparing series of two spatial patterns)	visuo-spatial task (Judgement of line orientation test [JOLO])	—	—
Hauer et al 2003 (patients without CI)	Within-subject design	Geriatrics patients with history of severe falls (without CI)	20	82.6	2	18	Standing	Balance Performance Monitor	Serial-2 addition	Serial-7 subtraction	—	—

2017a, b; Riley et al. 2003, 2005; Salavati et al. 2009; Vuillerme et al. 2006, 2000). The study by Brauer et al. used two cognitive tasks each with its simple and complex variants on the same subjects and are treated as separate studies and designated as a and b in the meta-analysis (Brauer et al. 2004). Similarly, the study by Riley and colleagues used two cognitive tasks each with its simple and complex variants on different participants and are also treated as separate studies and designated a and b in the meta-analysis (Riley et al. 2005). Separate meta-analysis was conducted for healthy young adults and patients with neurological condition (stroke). The aim of the analysis was to demonstrate the effect of cognitive task complexity on postural stability during dual tasking and thus sub-group analysis comparing

Table 2 (continued)



Hauer et al 2003 (patients with CI)	Within-subject design	Geriatrics patients with history of severe falls (with CI)	20	83.2	2	18	Standing	Balance Performance Monitor	Serial-2 addition	Serial-7 subtraction	↓ postural stability	↓ postural stability
Holmes et al 2010	Within-subject design	Patients with idiopathic PD	12	64.0	8	4	Standing	Force plate	numerical recitation task (counting from one to five in a looped sequence)	Engaging in a monologue (describing a familiar place)	—	↓ postural stability
Salvati et al 2009	Within-subject design	Non-specific LBP	22	26.1	13	9	Standing on rigid surface (EO, EC) Standing on foam surface (EC)	Force plate	Backward digit span task (half of the digits of the difficult task)	Backward digit span task (maximum number of digits recalled at baseline plus one)	—	↑ postural stability
Mehdizadeh et al 2018	Within-subject design	Stroke survivors	19	51.5	9	10	Standing on rigid surface (EO, EC) Standing on foam surface (EC)	Force plate	Backward digit span task (half of the digits of the difficult task)	Backward digit span task (maximum number of digits recalled at baseline plus one)	↑ postural stability (Standing on foam surface (EC))	↑ postural stability (Standing on foam surface (EC))
Mehdizadeh et al 2015	Within-subject design	Stroke survivors	19	51.5	9	10	Standing on rigid surface (EO, EC) Standing on foam surface (EC)	Force plate	Backward digit span task (half of the digits of the difficult task)	Backward digit span task (maximum number of digits recalled at baseline plus one)	↑ postural stability (Standing on foam)	↑ postural stability (Standing on foam)
Negahban et al 2017	Within-subject design	Stroke survivors	22	55.8	15	7	Standing	Force plate	Congruent colour-word stroop task	Incongruent colour-word stroop task	↓ postural stability	↓ postural stability
Yardley et al 2001 (Spatial task)	Within-subject design	Patients with vestibular disorder	48	46.65	16	standing with eyes closed on a stable platform standing with eyes closed on a	EquiTest system.	Equilibrium score Postural sway	Spatial auditory discrimination tasks	Spatial categorisation of a numerical stimulus.	—	—
						destabilised, "sway referenced" platform.						
Yardley et al 2001 (non-spatial task)	Within-subject design	Patients with vestibular disorder	48	46.65	16	standing with eyes closed on a stable platform standing with eyes closed on a destabilised, "sway referenced" platform.	EquiTest system.	Equilibrium score Postural sway	Non-spatial auditory discrimination tasks	Non-spatial categorisation of a numerical stimulus	—	—

↓= Significant decrease; ↑=Significant increase; —= No significant change; * = Significant difference between simple and complex cognitive tasks (higher in the task denoted by asterisk); RT= Reaction time; EO = Eyes opened; EC = Eyes closed; PD= Parkinson's disease, CI = Cognitive impairment; LBP = Low back pain; Av = Average; M =Male; F= Female, CPA= Compensatory postural adjustment

↓ = Significant decrease; ↑ = Significant increase; – = No significant change; * = Significant difference between simple and complex cognitive tasks (higher in the task denoted by asterisk); *RT* reaction time; *EO* eyes opened; *EC* eyes closed; *PD* Parkinson's disease, *CI* cognitive impairment; *LBP* low back pain; *Av* average; *M* male; *F* female, *CPA* compensatory postural adjustment

simple and complex cognitive tasks sub-groups was used. In the stroke patients, the postural task used in the included studies was quiet standing with feet shoulder-width apart and eyes open. In the healthy young adults, in addition to quiet standing, data from studies with more challenging postural tasks were also pooled. Additionally, since studies used different and multiple outcome measures, separate meta-analyses were carried out for the different outcome measures, which included centre of pressure (COP) sway area, sway velocity, sway variability, total sway path length and sway frequency in the different categories of participants.

Effects of cognitive task complexity on postural stability during quiet standing in healthy young adults

To investigate this effect, studies comparing the effect of simple and complex cognitive tasks on postural stability in healthy young adults during quiet standing (standing with feet shoulder-width apart and eyes open) were pooled. The different COP sway measures used in the included studies were sway area (Bustillo-Casero et al. 2017; Hauer et al. 2003; Huxhold et al. 2006), sway velocity (Bustillo-Casero et al. 2017; Salavati et al. 2009; Vuillerme et al. 2000), anterior–posterior (AP) sway variability (Dault et al. 2001a, b; Dault et al. 2003; Salavati et al. 2009), medio-lateral (ML) sway variability (Dault et al. 2001a, b; Dault et al. 2003; Huxhold et al. 2006; Salavati et al. 2009), AP sway frequency and ML sway frequency (Dault et al. 2001a, b; Dault et al. 2003). Five studies that assessed the effect of cognitive task complexity on dual-task postural stability in healthy young adults during quiet standing were not included in the meta-analyses because they did not provide adequate descriptive data (mean and standard deviation) to calculate effect sizes (Bernard-Demanze et al. 2009; Dault et al. 2001a, b; Onofrei et al. 2020) or used outcome measures different from COP sway (Cleveland clinic postural stability index and sensory organization test score) (Linder et al. 2019; Mujdeci et al. 2015).

Analyses showed that complex cognitive tasks resulted in slightly larger effect sizes in two of the outcome measures (Sway velocity & AP sway frequency), whereas simple tasks had slightly larger effect sizes for Sway area, AP sway variability, ML sway variability and ML sway frequency. However, the difference between the effect of simple and complex cognitive tasks was not statistically significant for all different sway measures (test for subgroup differences $P > 0.1$) (Table 3A). The direction of effect was also the same for both simple and complex cognitive tasks (Fig. 2a–d). Simple cognitive tasks led to significant reduction of AP and ML sway variability (AP sway variability; SMD 0.283, 95% CI 0.028–0.537, $P=0.029$, ML sway variability; SMD 0.274, 95% CI 0.029–0.518, $P=0.028$) (Fig. 2b, c). In contrast, both simple and complex tasks led to significant increase in AP sway frequency (Simple task: MD − 0.044, 95% CI − 0.084 to − 0.003, $P=0.036$; Complex task: MD -0.065, 95% CI − 0.101 to − 0.029, $P=0.000$) (Fig. 2d). The reductions in sway area (simple & complex task), sway velocity (simple & complex task), AP sway variability (complex task), ML sway variability (complex task) and increase in ML sway frequency (simple & complex task) were all non-significant. Substantial heterogeneity was only observed between studies assessing sway area using simple cognitive tasks ($I^2=63\%$, $P=0.099$).

Effects of cognitive task complexity on postural stability during challenging postural tasks in healthy young adults

The effect of cognitive task complexity on postural stability while maintaining more difficult postural tasks such as standing with eyes closed, standing with feet together, tandem stance, semi-tandem stance, standing on foam surface, or single leg stance was also assessed in healthy young adults in some studies. Data from these studies were included in meta-analyses across various COP sway measures including sway area (Bustillo-Casero et al. 2017; Richer, et al. 2017a, b; Vuillerme and Vincent 2006), AP and ML sway velocity (Bustillo-Casero et al. 2017; Olivier et al. 2010; Richer et al. 2017a, b), total sway path length (Bohle et al. 2019; Brauer et al. 2004; Pellecchia 2003), AP sway variability (Brauer et al. 2004; Dault et al. 2003; Richer, et al. 2017a, b; Riley et al. 2003; Salavati et al. 2009), ML sway variability (Brauer et al. 2004; Riley et al. 2005; Salavati et al. 2009), AP sway frequency (Brauer et al. 2004; Vuillerme and Vincent 2006) and ML sway frequency (Brauer et al. 2004; Richer, et al. 2017a, b; Vuillerme and Vincent 2006). Six other studies also used a challenging postural task as the primary task in healthy young adults but were unable to be included in the analysis due to inadequate descriptive data (Barra et al. 2006; Zhang et al. 2019) and use of outcome measures other than COP sway (postural stability index score, centre of mass movement using 2-D motion analysis, proportion of time spent in balance correction and centre of pressure minus centre of gravity using stabilogram diffusion analysis) (Oliaei et al. 2018; Rebold et al. 2017; Rougier and Bonnet 2016; Swan et al. 2007).

The results of the meta-analyses on the effect of simple and complex cognitive tasks during a challenging postural task on sway area, sway variability, sway velocity, total sway path length and sway frequency are reported in Fig. 3a–e and Table 3B. Sub-group analysis did not show significant difference between the effect of simple and complex cognitive tasks for any of the sway measures ($P > 0.1$) (Table 3B). Simple cognitive tasks led to a significant increase in AP sway velocity (MD − 1.042, 95% CI − 1.894 to − 0.190, $P=0.017$). The effect of complex cognitive tasks on AP sway velocity on the other hand, was a non-significant increase (MD − 0.719 95% CI − 1.564–0.126, $P=0.095$). However, an outlier (Bustillo-casero 2017-Single leg stance) was identified, and the effect became statistically significant after removing it (MD − 0.854 95% CI − 1.656 to − 0.048, $P=0.038$). Similarly, the effect of complex cognitive tasks showed a trend toward significant increase in total sway path length (MD − 100.177, 95% CI − 201.141–0.788, $P=0.052$). This also reached statistical significance after removing an outlier (Bohle 2019) from the analysis (MD − 139.364, 95% CI − 218.947 to − 59.782, $P=0.001$). Another outcome measure that significantly increased during dual tasking using complex cognitive tasks is ML sway frequency (MD − 0.080, 95% CI − 0.118 to − 0.041, $P=0.000$). In contrast, dual tasking using complex cognitive tasks led to significant decrease in AP sway variability (SMD 0.387, 95% CI 0.110–0.664, $P=0.006$). The changes in sway area (simple & complex tasks), ML sway velocity (simple & complex), Total sway path (simple task), AP sway variability (simple task), ML sway variability (simple & complex tasks), AP sway frequency (simple & complex tasks) and ML sway frequency (simple task) were all not statistically significant even after removing outliers where appropriate. Heterogeneity is more than 60% in half of the sway measures here (Table 3B). The high level of heterogeneity in many sway measures could be related to the different postural positions used in the included studies which vary in their level of difficulty.

Effects of cognitive task complexity on postural stability during quiet standing in Stroke patients

Only two studies provided adequate descriptive data (mean and SD) to investigate the effect of cognitive task complexity on sway area during dual tasking in stroke patients and were included in the meta-analysis (Bourlon et al. 2014; Negahban et al. 2017). Two other studies with stroke patients were not included because the studies did not report adequate descriptive data to be used in meta-analysis (Mehdizadeh et al. 2018, 2015).

Other studies involving patient groups are not included in the meta-analysis because, in addition to involving patients with different disease conditions, different postural stability outcome measures as well as different balance tasks were used in the different studies. These include idiopathic Parkinson's disease (postural task: Quiet standing; Outcome measures: percentage of base of support in AP and ML directions and Total length of COP in the horizontal plane) (Holmes et al. 2010), patients with vestibular disorders (postural task: Standing with eyes closed on stable and unstable platforms; Outcome measures: Equilibrium score, Mean COP velocity and sway variability-direction not stated) (Yardley et al. 2001), geriatric patients with history of severe falls with or without cognitive impairments (postural task: Quiet standing; Outcome measures: AP and ML sway angle deviations and sway area) (Hauer et al. 2003), young adults with severe brain injury (postural task: Standing in step stance position; Outcome measures: COP total distance, AP and ML sway variability) (Brauer et al. 2004) and young adults with non-specific low back pain (postural task: Standing on foam and rigid surfaces; Outcome measures: phase plane portrait, mean total velocity and AP and ML sway variability).

Analysis of the results in stroke patients revealed non-significant effects for both the simple (MD − 17.227, 95% CI − 161.278−126.823, $P = 0.815$) and complex tasks (MD 34.719, 95% CI − 233.784−303.223, $P = 0.800$) on sway area (Fig. 4). The test for sub-group difference comparing the effect of simple and complex cognitive tasks was also non-significant ($P > 0.1$) (Table 3C).

Effect of dual tasking on cognitive performance

Like postural stability, cognitive task performance can also change during dual tasking (when the cognitive task is performed in the standing position) compared to single task (when the cognitive task is performed in the sitting position). Out of the 33 studies included in this review, only 13 studies analyzed and reported the difference in cognitive performance between single task and dual tasking using quiet standing or challenging postural tasks (supplementary material 3) (Barra et al. 2006; Brauer et al. 2004; Bustillo-Casero et al. 2017; Dault et al. 2001a, b; Dault et al. 2001a, b; Dault et al. 2003; Hauer et al. 2003; Huxhold et al. 2006; Linder et al. 2019; Negahban et al. 2017; Salavati et al. 2009; Swan et al. 2007; Yardley et al. 2001).

In healthy young adults, the effect of dual tasking using a quiet standing position on cognitive performance was reported by eight studies. In seven of these studies, performance of both simple and complex cognitive tasks did not change significantly during dual tasking (Bustillo-Casero et al. 2017; Dault et al. 2001a, b; Dault et al. 2001a, b; Dault et al. 2003; Huxhold et al. 2006; Linder et al. 2019; Salavati et al. 2009). In the remaining one study (Hauer et al. 2003), dual tasking in a quiet standing position led to a significant reduction of the performance of the simple cognitive task while the performance of the complex cognitive task remained unaffected. The effect of dual tasking in challenging postural positions on cognitive performance in healthy young adults was reported in nine studies, six of which found no significant change in the performance of both simple and complex cognitive tasks during dual tasking (Brauer et al. 2004; Bustillo-Casero et al. 2017; Dault et al. 2001a, b; Dault et al. 2001a, b; Dault et al. 2003; Linder et al. 2019). In one study, the performance of both simple and complex Brook's spatial and nonsense task decreased significantly when performed while standing with feet together and eyes closed compared to single task performance in the sitting position (Swan et al. 2007). Finally, one study found a significant decrease of simple cognitive task performance during dual tasking (Barra et al. 2006), while the remaining one study found a significant decrease in complex cognitive task performance (Salavati et al. 2009).

Only one study analyzed and reported the effect of dual tasking in cognitive performance in healthy older adults (Huxhold et al. 2006). In this study, performance of both simple and complex cognitive tasks while sitting did not change significantly when the same tasks were performed in a quiet standing position.

Robustness analysis of the effect of cognitive task complexity on postural stability

To accurately assess attentional costs associated with postural control, it is essential to have access to performance of both the postural and cognitive tasks in both single-task and dual-task conditions (i.e., 4 different conditions) (Boisgontier et al. 2013). Therefore, we re-analyzed the data in a robustness analysis including only those studies that reported performance in both postural and cognitive tasks under both single and dual task conditions.

Table 3 Effect of cognitive task complexity on dual task postural stability in healthy young adults (quiet standing and challenging postural tasks) and in stroke patients (quiet standing)

Outcome measure	comparison	Sample		Effect size				Heterogeneity		
		Number of studies	Number of subjects	Estimate	Lower limit	Upper limit	p-value	P-value	I^2, %	Tau^2
a. Effect of cognitive task complexity on dual task postural stability during quiet standing in healthy young adults										
Sway area	Simple task	3	55	4.814	-12.413	22.041	0.584	0.270	24%	55.948
	Complex task	3	55	1.636	-16.151	19.422	0.857	0.553	0	0.000
	Total between							0.740		
Sway velocity	Simple task	3	43	0.248	-0.391	0.888	0.447	0.406	0	0.000
	Complex task	3	43	0.290	-0.350	0.930	0.374	0.509	0	0.000
	Total between							0.928		
AP Sway variability	Simple task	3	62	0.283	0.028	0.537	0.029	0.788	0%	0.000
	Complex task	3	62	0.240	-0.013	0.492	0.063	0.998	0%	0.000
	Total between							0.427		
								0.814		
ML Sway variability	Simple task	4	82	0.274	0.029	0.518	0.028	0.308	16.73%	0.010
	Complex task	4	82	0.246	-0.027	0.520	0.078	0.210	33.74%	0.026
	Total between							0.878		
AP Sway frequency	Simple task	2	40	-0.044	-0.084	-0.003	0.036	0.818	0%	0.000
	Complex task	2	40	-0.065	-0.101	-0.029	0.000	0.784	0%	0.000
	Total between							0.437		
ML Sway frequency	Simple task	2	40	-0.050	-0.146	0.046	0.307	0.099	63%	0.003
	Complex task	2	40	-0.046	-0.112	0.021	0.177	0.185	43%	0.001
	Total between							0.894		
b. Effect of cognitive task complexity on dual task postural stability during challenging balance tasks in healthy young adults										
Sway area	Simple task	4	68	41.203	-23.509	105.916	0.212	0.037	65%	2797.215
	Complex task	4	68	75.418	-18.804	169.641	0.117	0.000	85%	7713.748
	Total between							0.569		
AP Sway velocity	Simple task	5	73	-1.042	-1.894	-0.190	0.017	0.600	0%	0.000
	Complex task	5	73	-0.719	-1.564	0.126	0.095	0.344	11%	0.104
	Total between							0.579		
ML Sway velocity	Simple task	5	73	-0.592	-1.509	0.325	0.206	0.136	43%	0.444
	Complex task	5	73	-0.378	-1.482	0.726	0.502	0.031	62%	0.920
	Total between							0.726		
Total Sway path	Simple task	4	88	-18.540	-41.997	4.917	0.121	0.759	0%	0.000
	Complex task	4	88	-100.177	-201.141	0.788	0.052	0.000	90%	9356.496
	Total between							0.140		
AP Sway variability	Simple task	7	152	0.198	-0.107	0.503	0.202	0.003	70%	0.119
	Complex task	7	152	0.387	0.110	0.664	0.006	0.013	63%	0.087
	Total between							0.363		
ML Sway variability	Simple task	6	124	0.120	-0.057	0.298	0.183	0.183	0%	0.000
	Complex task	6	124	0.059	-0.204	0.322	0.661	0.661	53.12%	0.058
	Total between							0.701		
AP Sway frequency	Simple task	3	53	-0.110	-0.444	0.224	0.519	0.041	69%	0.059
	Complex task	3	53	-0.253	-0.526	0.021	0.070	0.111	54%	0.034
	Total between							0.243		
ML Sway frequency	Simple task	4	78	-0.047	-0.108	0.014	0.130	0.030	66%	0.002
	Complex task	4	78	-0.080	-0.118	-0.041	0.000	0.309	16%	0.000
	Total between							0.246		
c. Effect of cognitive task complexity on dual task postural stability during quiet standing in Stroke										
Sway area	Simple task	2	52	-17.227	-161.278	126.823	0.815	0.189	42%	4547.718
	Complex task	2	52	34.719	-233.784	303.223	0.800	0.012	84%	53086.749
	Total between							0.745		

Effect sizes- Effect sizes were calculated as differences in means (MD) for sway area, velocity, total sway path and frequency. Effect sizes for sway variability were calculated as standardized differences in mean (SMD).

Total between- The differences across subgroups were assessed using a fixed-effects model, while effects within subgroups were computed using a random-effects model.

Table 3 (continued)

Effect sizes-Effect sizes were calculated as differences in means (MD) for sway area, velocity, total sway path and frequency. Effect sizes for sway variability were calculated as standardized differences in mean (SMD)

Total between The differences across subgroups were assessed using a fixed-effects model, while effects within subgroups were computed using a random-effects model

In healthy young adults during quiet standing, six studies that compared the effect of simple and complex cognitive tasks on sway area, sway velocity, sway variability, sway frequency and reported the corresponding effect of dual tasking on cognitive performance are included in this analysis (Bustillo-Casero et al. 2017; Dault et al. 2001a, b; Dault et al. 2003; Hauer et al. 2003; Huxhold et al. 2006; Salavati et al. 2009). Similar to the first analysis, there was no significant difference between the effect of simple and complex cognitive tasks on postural stability during quiet standing in healthy young adults (test for subgroup differences $P > 0.1$). Simple cognitive tasks led to significant reduction of AP and ML sway variability (AP sway variability; SMD 0.283, 95% CI 0.028–0.537, $P=0.029$, ML sway variability; SMD 0.274, 95% CI 0.029–0.518, $P=0.028$) (supplementary materials 4 and 5). In contrast, both simple and complex tasks led to significant increase in AP sway frequency (Simple task: MD − 0.044, 95% CI − 0.084 to − 0.003, $P=0.036$; Complex task: MD − 0.065, 95% CI − 0.101 to − 0.029, $P=0.000$). The reductions in sway area (simple and complex task), sway velocity (simple and complex task), AP sway variability (complex task), ML sway variability (complex task) and increase in ML sway frequency (simple & complex task) were all non-significant.

During challenging postural conditions, four studies reported the effect of dual tasking on both postural and cognitive performance and are included in this analysis (Brauer et al. 2004; Bustillo-Casero et al. 2017; Dault et al. 2003; Salavati et al. 2009). Similarly, subgroup analysis comparing the effect of simple and complex cognitive tasks on various sway measures (sway area, AP & ML sway velocity, total sway path, AP & ML sway variability and AP & ML sway frequency) revealed no statistically significant difference ($P > 0.1$) (supplementary material 4). The effect of dual tasking using complex cognitive tasks on total sway path showed a trend toward significant increase (MD − 149.865, 95% CI − 300.565–0.834, $P=0.051$). Complex cognitive tasks led to significant increase in both AP and ML sway frequency (AP sway frequency: MD − 0.450, 95% CI − 0.776 to − 0.124, $P=0.007$; ML sway frequency: MD − 0.127, 95% CI − 0.226 to − 0.028, $P=0.012$) (supplementary materials 4, 6). In contrast, dual tasking using complex cognitive tasks led to significant reduction in AP sway variability (SMD 0.281, 95% CI 0.083–0.478, $P=0.005$). The change in sway area (simple and complex cognitive tasks), AP and ML sway velocity (simple and complex cognitive tasks), ML sway variability (simple and complex cognitive tasks), total sway path (simple cognitive tasks), AP sway variability (simple cognitive tasks), AP sway frequency (simple cognitive tasks) and ML sway frequency (simple cognitive tasks) were not statistically significant.

We were unable to conduct a robustness analysis in Stroke patients as only one study reported the effect of dual tasking on both postural and cognitive performance in this group of participants (Negahban et al. 2017).

Narrative synthesis of the effect of cognitive task complexity on postural stability in healthy old adults

We are unable to conduct meta-analysis for the studies involving healthy older adults due to inadequate descriptive data and different postural task or outcome measures used. Therefore, a brief narrative synthesis of the result in this category of participants based on the test of statistical significance and effect direction reported in the individual studies as summarized in Table 2 is provided.

Five studies compared the effect of simple and complex cognitive tasks on postural stability during dual tasking in older adults (Bernard-Demanze et al. 2009; Bohle et al. 2019; Holmes et al. 2010; Huxhold et al. 2006; Lajoie et al. 2017). However, because the study by Lajoie et al. tested two types of cognitive tasks (discrete and continuous tasks) each with it simple and complex variants, the number of studies increased to six. While quiet standing was used as postural task in three studies, the studies by Lajoie et al. and Bohle et al. used more challenging standing with feet together and semi-tandem stance on an unstable surface respectively. Similarly, in addition to quiet standing, Bernerd-Demanze et al. included a dynamic postural position. Performing dual tasking using simple cognitive tasks while maintaining quiet standing did not affect postural stability in one study (Holmes et al. 2010). In the remaining two studies that used a quiet standing position as the postural task, the effect of simple cognitive tasks was a significant decrease in postural stability (Bernard-Demanze et al. 2009) and a significant increase in postural stability, respectively (Huxhold et al. 2006). Contrarily, dual tasking using complex cognitive task led to significant decrease in postural stability in all the studies except one which shows an opposite result (Table 2). This decrease in postural stability during dual tasking using complex cognitive task was regardless of whether the participants were maintaining a quiet stance or a more challenging postural position. Finally, when the postural task is challenging, simple cognitive task led to decrease in stability in all but one study.

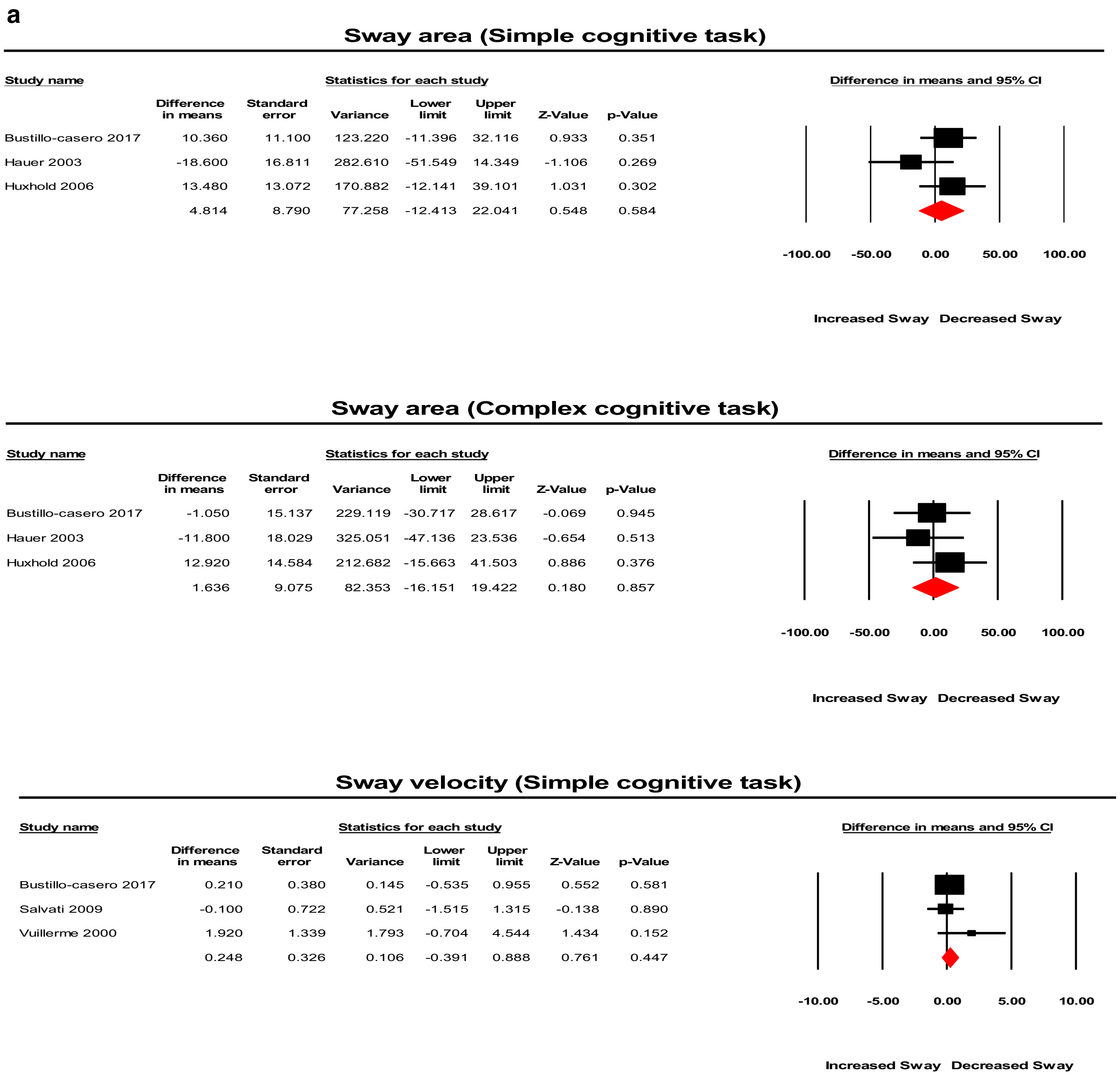
Discussion

The primary aim of this study was to investigate whether a simple cognitive task affects postural stability differently compared to a complex cognitive task during dual tasking. A U-shaped non-linear relationship was proposed between cognitive task complexity and postural stability during dual tasking by Huxhold and colleagues (2006). They suggested a simple, low-demanding secondary cognitive activity improved postural performance by serving as an external focus of attention which is represented by the decreasing range of the U-shape curve. In contrast, the raising part of the U-shaped interaction is caused by the complex cognitive tasks which place high demand on the cognitive resources thereby hindering postural control and increasing postural sway through cross-domain resource competition. However, after an extensive comparison across various posturographic measures from numerous studies pooled in a meta-analysis, our results did not reveal significant differences between the effects of simple and complex cognitive tasks on dual task postural stability. Although the effect sizes differ slightly between simple and complex cognitive tasks, the difference was not statistically significant. Importantly, the direction of the effect produced by both simple and complex cognitive tasks in healthy population was mainly the same depending on the postural challenge and the age of the participants. Essentially, no qualitative interaction exists between cognitive task complexity and dual task postural stability. Therefore, the U-shaped non-linear hypothesis is not supported by the results of this systematic review and meta-analysis, and cognitive task complexity does not appear to determine whether postural sway increases or decreases during dual tasking. However, a situation where simple cognitive task produced no change in postural stability, but a more complex task brings about a positive or negative change in postural stability depending on age or postural task challenge cannot be ruled out completely.

While maintaining a quiet standing position with eyes open, dual tasking produced effects which are consistent with decreased sway (improved postural stability) in healthy young adults. In older adults, the effect of dual tasking in the same standing position resulted in increased postural sway (decreased postural stability) especially when the cognitive task is complex. With an increasing balance challenge, however, dual tasking caused increased sway in both healthy young and older adults. The result of the meta-analysis in patients with pathological conditions is non-significant, and the overall result of the included studies did not indicate a single specific pattern. Thus, whether postural sway increases or decreases during dual tasking in healthy population may largely depend on the age of the participants and postural task challenge, not cognitive task complexity. This is in line with the position of Stins and Beek who argue that postural stability during dual tasking is only going to be affected negatively when the balance challenge is high or in individuals with reduced postural capacity due to aging or pathology, because these are the most likely scenarios where a conscious effort involving higher cortical functions is needed to regulate posture (Stins and Beek 2012).

As mentioned above, our results revealed that during quiet standing in healthy young adults, dual tasking led to decreased postural sway characterized by decreased sway variability and increased sway frequency. Two major hypotheses have been proposed to explain the decreased sway observed during dual tasking while maintaining quiet standing in healthy young adults (Ehrenfried et al. 2003; Polskaia and Lajoie 2016). According to the first hypothesis, dual tasking promotes a stiffening strategy leading to a tighter control of postural sway (Dault et al. 2003; Vuillerme et al. 2000; Vuillerme and Vincent 2006). This is based on previous research which suggests that if the body is modelled as an inverted pendulum, increased frequency and decreased variability of sway may be related to increased ankle stiffness evidenced by increased stiffness constant and increased muscle activity in the ankle musculature (Carpenter et al. 1999, 2001; Winter et al. 1998). However, in the studies by Carpenter and colleagues (Carpenter et al. 1999, 2001), which are cited by dual task studies to support the stiffness hypothesis based on their finding of increased sway frequency and decreased sway variability, measurement of balance was compared between standing quietly at the ground level and at the edge of an elevated surface 81 cm above ground level (postural threat). A follow-up study showed that an elevated position such as this which led to increased stiffness was also associated with increased conscious control of posture (Huffman et al. 2009). Therefore, in our view, increased stiffness control of balance is a less likely mechanism responsible for the decreased sway during dual tasking while standing quietly in young adults. In fact, other studies that have examined muscular activity around the ankle joint during dual-tasking have found either no effect or decrease in muscle activity (Rankin et al. 2000; Richer, et al. 2017a, b), thereby reducing support for this hypothesis.

The second hypothesis (constrained action hypothesis) suggests that the decreased sway during dual tasking in cases with minimal postural demand is the result of a shift to more automatic control of posture (Bernard-Demanze et al. 2009; Polskaia and Lajoie 2016; Richer and Lajoie 2020; Richer et al. 2017a, b). Maintaining quiet standing in young adults with an intact sensorimotor system is a well-learned self-organized postural behaviour that can progress automatically under the control of brainstem and spinal cord neural circuits



Sway area (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017	10.360	11.100	123.220	-11.396	32.116	0.933	0.351
Hauer 2003	-18.600	16.811	282.610	-51.549	14.349	-1.106	0.269
Huxhold 2006	13.480	13.072	170.882	-12.141	39.101	1.031	0.302
	4.814	8.790	77.258	-12.413	22.041	0.548	0.584

Sway area (Complex cognitive task)

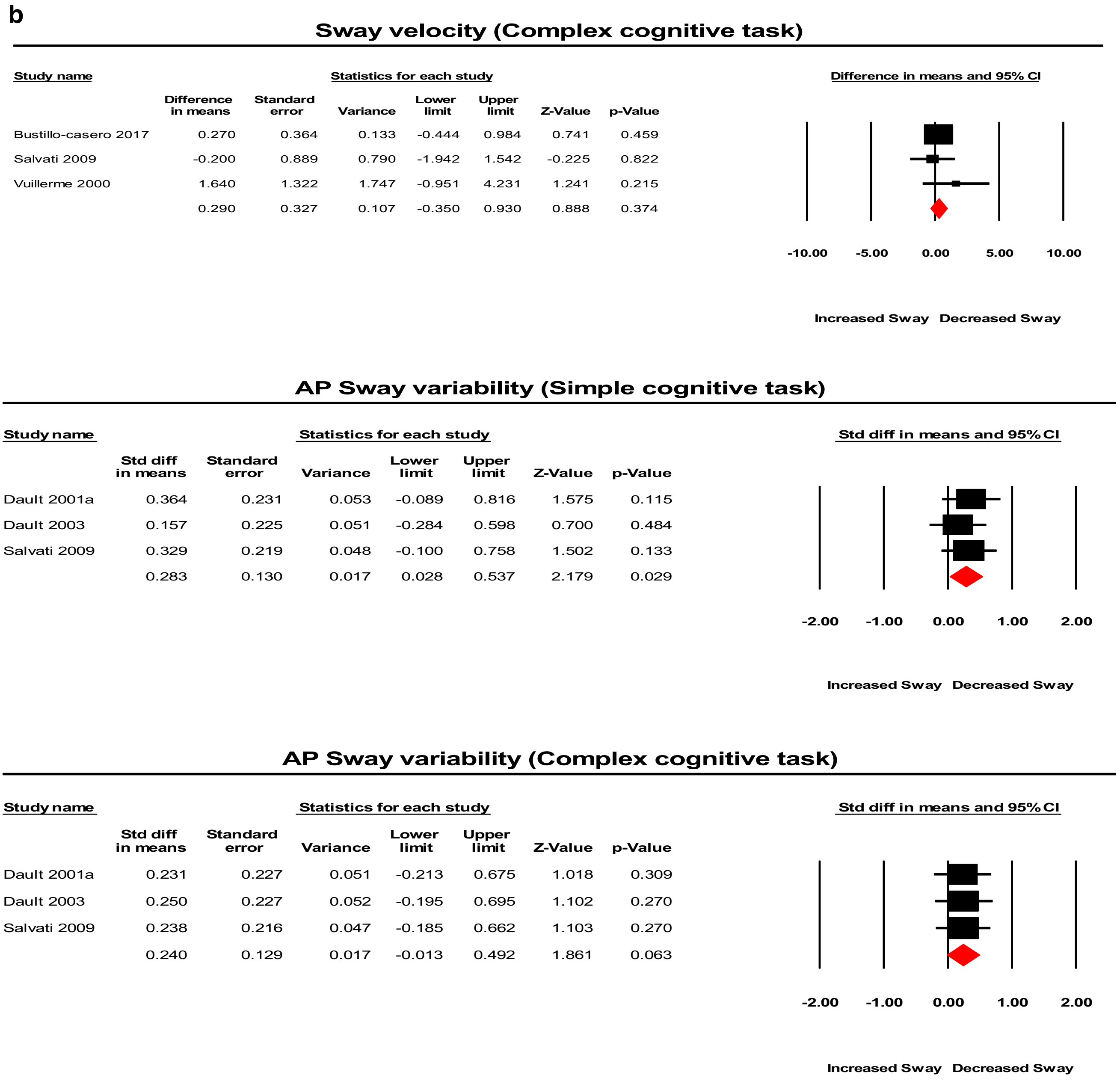
Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017	-1.050	15.137	229.119	-30.717	28.617	-0.069	0.945
Hauer 2003	-11.800	18.029	325.051	-47.136	23.536	-0.654	0.513
Huxhold 2006	12.920	14.584	212.682	-15.663	41.503	0.886	0.376
	1.636	9.075	82.353	-16.151	19.422	0.180	0.857

Sway velocity (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017	0.210	0.380	0.145	-0.535	0.955	0.552	0.581
Salvati 2009	-0.100	0.722	0.521	-1.515	1.315	-0.138	0.890
Vuillerme 2000	1.920	1.339	1.793	-0.704	4.544	1.434	0.152
	0.248	0.326	0.106	-0.391	0.888	0.761	0.447

Fig. 2 **a–d** Forest plots showing the effect of simple and complex cognitive tasks on dual task postural stability during quiet standing in healthy young adults. *AP* Antero-posterior; *ML* Mediolateral

(Takakusaki 2017; Winter et al. 1998). In dual-task experiments, participants are often encouraged to stand as still as possible during single task balance measurement forcing them to focus their attention in minimizing body sway (Vuillerme et al. 2000). According to the constrained action hypothesis, focusing attention on postural control in this situation may degrade the relatively automatic process leading to decreased efficiency and thus an increased sway (Richer and Lajoie 2020; Vuillerme and Nafati 2007; Wulf and Prinz 2001). However, when a secondary cognitive task is introduced, the focus of attention will shift from postural control to cognitive performance limiting the interference with the efficient automatic motor control process thereby leading to decreased sway (Polskaia and Lajoie 2016). Therefore, the higher frequency, low variability sway observed during dual tasking in a quiet standing position may reflect a coordinated and well-organized automatic sensorimotor integration process with more active degrees of freedom (McNevin et al. 2003; Polskaia and Lajoie 2016; Wulf et al. 2001). The non-significant change in cognitive performance during dual tasking in quiet standing position reported by majority of the included studies lend further support to this interpretation.



b

Sway velocity (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017	0.270	0.364	0.133	-0.444	0.984	0.741	0.459
Salvati 2009	-0.200	0.889	0.790	-1.942	1.542	-0.225	0.822
Vuillerme 2000	1.640	1.322	1.747	-0.951	4.231	1.241	0.215
	0.290	0.327	0.107	-0.350	0.930	0.888	0.374

AP Sway variability (Simple cognitive task)

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	0.364	0.231	0.053	-0.089	0.816	1.575	0.115
Dault 2003	0.157	0.225	0.051	-0.284	0.598	0.700	0.484
Salvati 2009	0.329	0.219	0.048	-0.100	0.758	1.502	0.133
	0.283	0.130	0.017	0.028	0.537	2.179	0.029

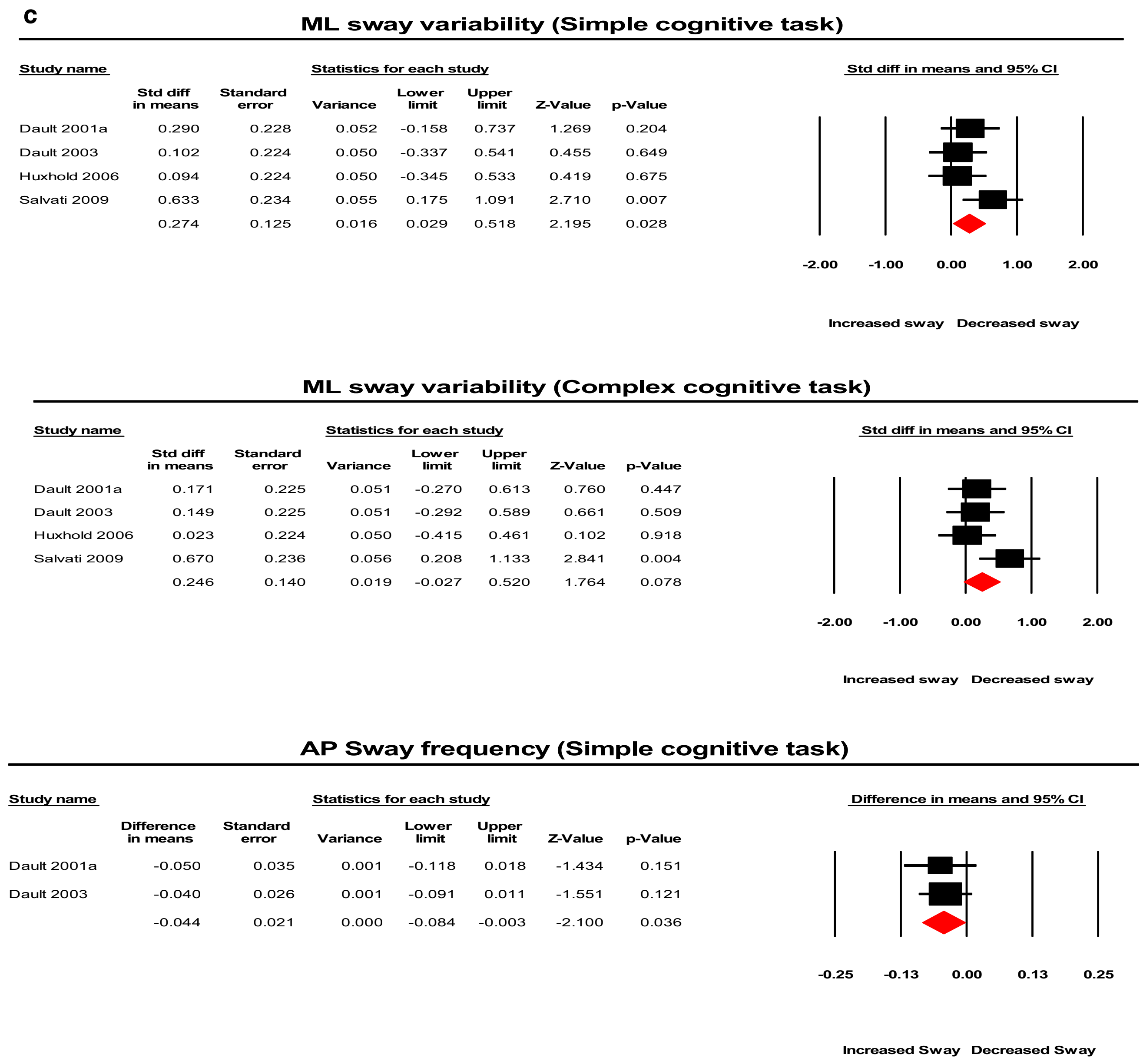
AP Sway variability (Complex cognitive task)

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	0.231	0.227	0.051	-0.213	0.675	1.018	0.309
Dault 2003	0.250	0.227	0.052	-0.195	0.695	1.102	0.270
Salvati 2009	0.238	0.216	0.047	-0.185	0.662	1.103	0.270
	0.240	0.129	0.017	-0.013	0.492	1.861	0.063

Fig. 2 (continued)

It implied that the participants focused their attention on cognitive tasks thereby maintaining cognitive performance while allowing postural control to take place automatically. Indeed, when we conducted a robustness analysis including only those studies that report the effect of dual tasking on cognitive performance, the findings remain the same (decreased sway).

With increasing balance challenge in healthy young adults e.g., single leg stance, our results revealed changes in sway parameters which is consistent with increased sway (decreased postural stability) during dual tasking. Total sway path significantly increased during dual tasking using complex cognitive task while anteroposterior sway velocity increased regardless of the complexity of the cognitive task. In contrast, sway variability decreased when complex cognitive task is used. Increased variability of posture or gait is suggested to imply a more cortically controlled effort of maintaining stability using cognitive resources (Leach et al. 2018; Yogev-Seligmann et al. 2008). Thus, the decreased sway variability during dual tasking in this case may represent a lack of conscious effort to control postural stability since attention is diverted toward the performance of the



ML sway variability (Simple cognitive task)

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	0.290	0.228	0.052	-0.158	0.737	1.269	0.204
Dault 2003	0.102	0.224	0.050	-0.337	0.541	0.455	0.649
Huxhold 2006	0.094	0.224	0.050	-0.345	0.533	0.419	0.675
Salvati 2009	0.633	0.234	0.055	0.175	1.091	2.710	0.007
	0.274	0.125	0.016	0.029	0.518	2.195	0.028

ML sway variability (Complex cognitive task)

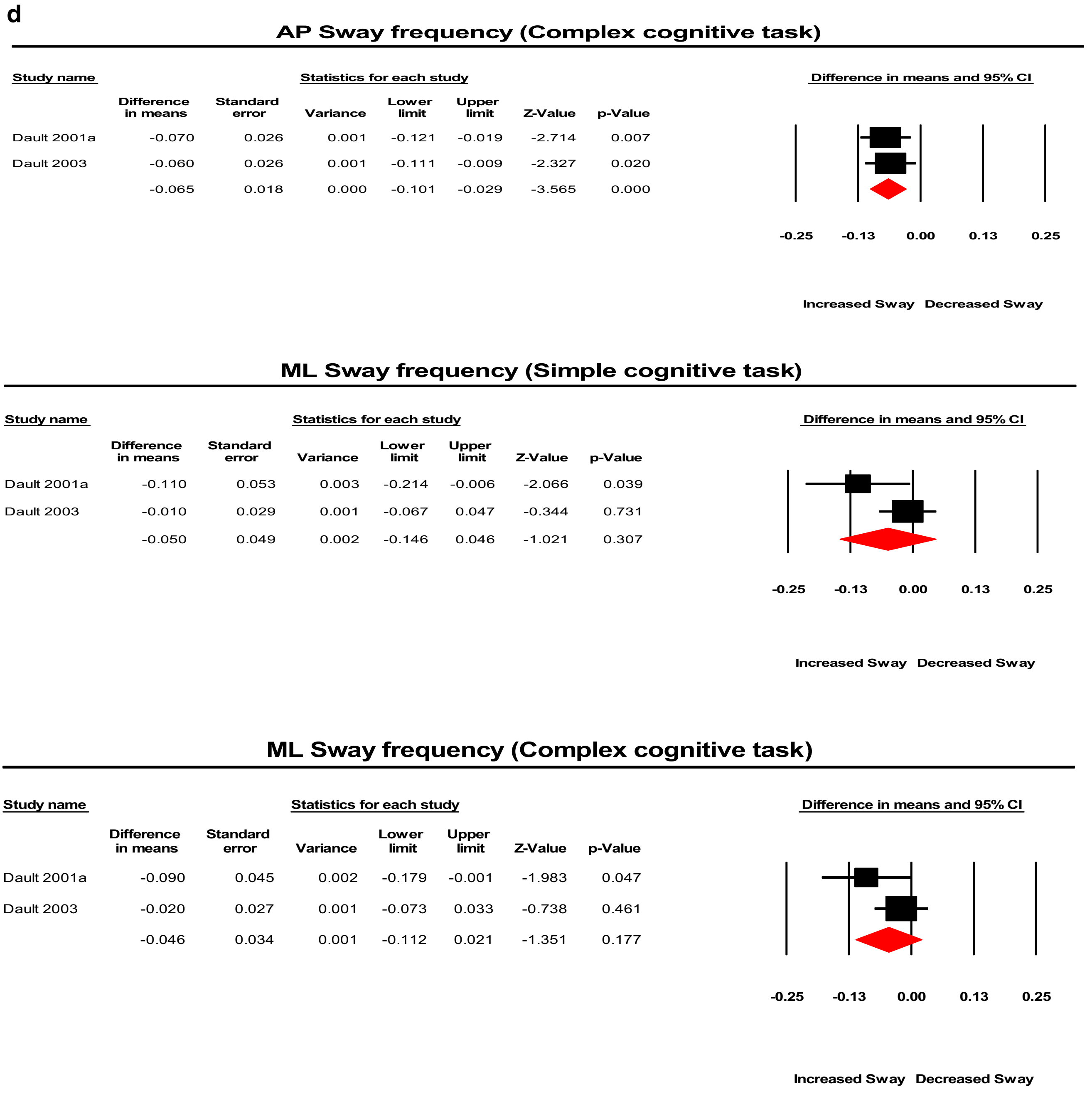
Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	0.171	0.225	0.051	-0.270	0.613	0.760	0.447
Dault 2003	0.149	0.225	0.051	-0.292	0.589	0.661	0.509
Huxhold 2006	0.023	0.224	0.050	-0.415	0.461	0.102	0.918
Salvati 2009	0.670	0.236	0.056	0.208	1.133	2.841	0.004
	0.246	0.140	0.019	-0.027	0.520	1.764	0.078

AP Sway frequency (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	-0.050	0.035	0.001	-0.118	0.018	-1.434	0.151
Dault 2003	-0.040	0.026	0.001	-0.091	0.011	-1.551	0.121
	-0.044	0.021	0.000	-0.084	-0.003	-2.100	0.036

Fig. 2 (continued)

cognitive task leading to increase in both sway velocity and total sway path length or a decrease in postural stability. This phenomenon whereby postural sway increased during dual tasking while maintaining a challenging postural position can be explained according to the cross domain-resource competition hypothesis. Attentional demand for postural control has been shown to increase with increasing balance challenge (Lajoie et al. 1993) and therefore in such instances, postural control may no longer be automatic (Takakusaki 2017). Based on the cross-domain resource-competition hypothesis dual-tasking under a challenging balance condition would lead to cognitive-motor interference causing a decrease in postural stability since both the cognitive and motor tasks, being attention-demanding, would compete for the limited attentional resources for their control (Wollesen et al. 2016). In other words, the increased postural sway observed during challenging balance tasks in healthy young adults might be because they channeled their available cognitive resources toward the performance of the cognitive task leaving inadequate resources for conscious control of posture. Indeed, cognitive performance was not significantly affected by dual tasking in many of the studies that reported effect of dual tasking in a challenging postural position on cognitive performance. However, some of the included



AP Sway frequency (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	-0.070	0.026	0.001	-0.121	-0.019	-2.714	0.007
Dault 2003	-0.060	0.026	0.001	-0.111	-0.009	-2.327	0.020
	-0.065	0.018	0.000	-0.101	-0.029	-3.565	0.000

ML Sway frequency (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	-0.110	0.053	0.003	-0.214	-0.006	-2.066	0.039
Dault 2003	-0.010	0.029	0.001	-0.067	0.047	-0.344	0.731
	-0.050	0.049	0.002	-0.146	0.046	-1.021	0.307

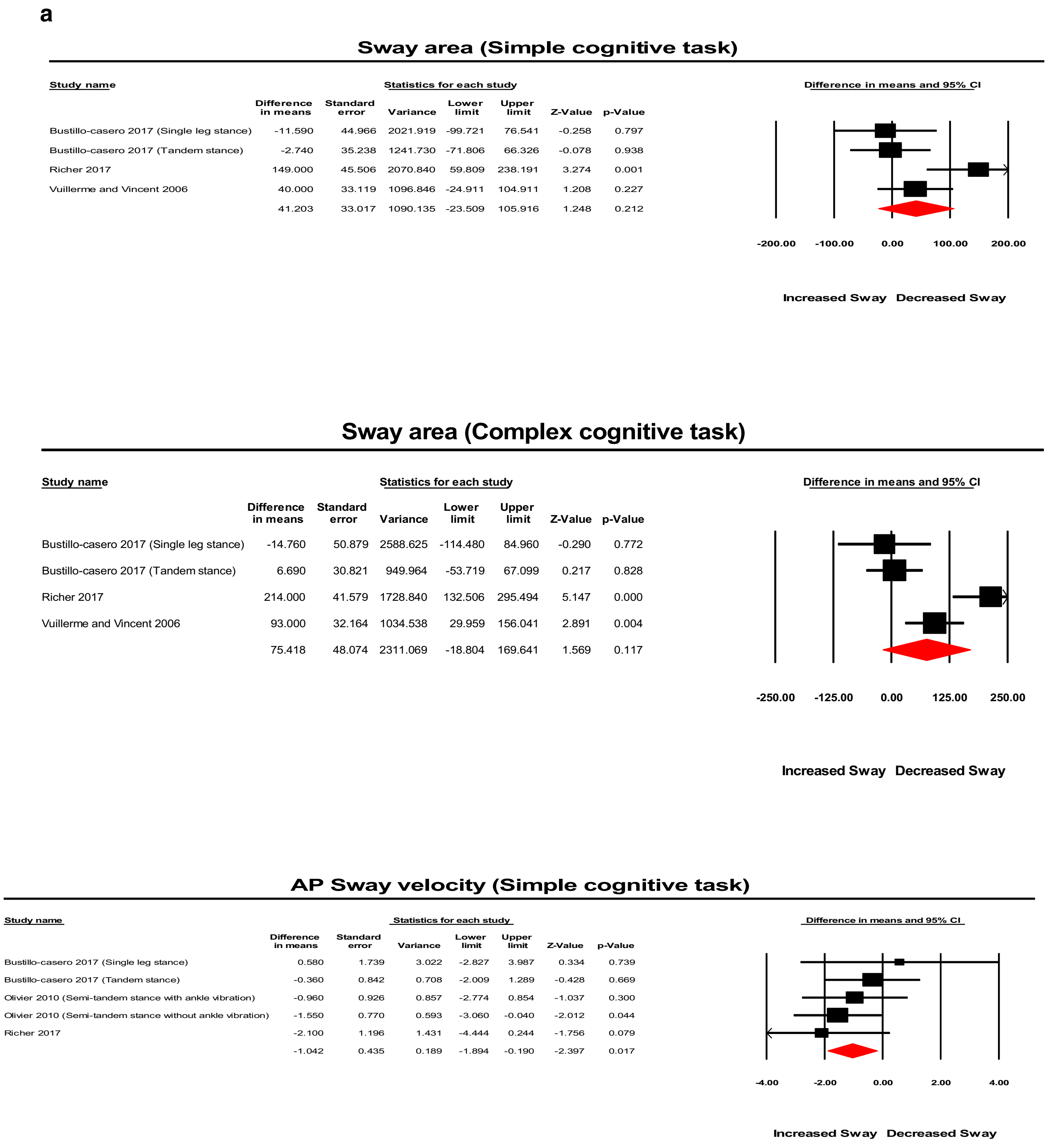
ML Sway frequency (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Dault 2001a	-0.090	0.045	0.002	-0.179	-0.001	-1.983	0.047
Dault 2003	-0.020	0.027	0.001	-0.073	0.033	-0.738	0.461
	-0.046	0.034	0.001	-0.112	0.021	-1.351	0.177

Fig. 2 (continued)

studies found a negative effect of dual tasking in challenging postural position on cognitive performance. Furthermore, in our robustness analysis, only total sway path showed a trend toward significant increase. Thus, during dual tasking in a challenging postural position, healthy young adults may prioritize either the cognitive task, leaving postural stability negatively affected by dual tasking or the postural task leaving the cognitive performance negatively affected. The choice of the task to prioritize was suggested to depend among other factors on the perceived threat safety (Ruffieux et al. 2015; Shumway-Cook et al. 1997; Yogev-Seligmann et al. 2012). When the level of threat is high (e.g., standing at the edge of a cliff), postural control would be prioritized, but in situations where the threat to stability is not potentially injurious, the cognitive task would be prioritized (Shumway-Cook et al. 1997).

In older adults, dual tasking during quiet standing led to increased postural sway especially when the cognitive task is complex. This is in line with the findings of a previous review article which suggest that the cognitive task should



Sway area (Simple cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	-11.590	44.966	2021.919	-99.721	76.541	-0.258	0.797
Bustillo-casero 2017 (Tandem stance)	-2.740	35.238	1241.730	-71.806	66.326	-0.078	0.938
Richer 2017	149.000	45.506	2070.840	59.809	238.191	3.274	0.001
Vuillerme and Vincent 2006	40.000	33.119	1096.846	-24.911	104.911	1.208	0.227
	41.203	33.017	1090.135	-23.509	105.916	1.248	0.212

Sway area (Complex cognitive task)

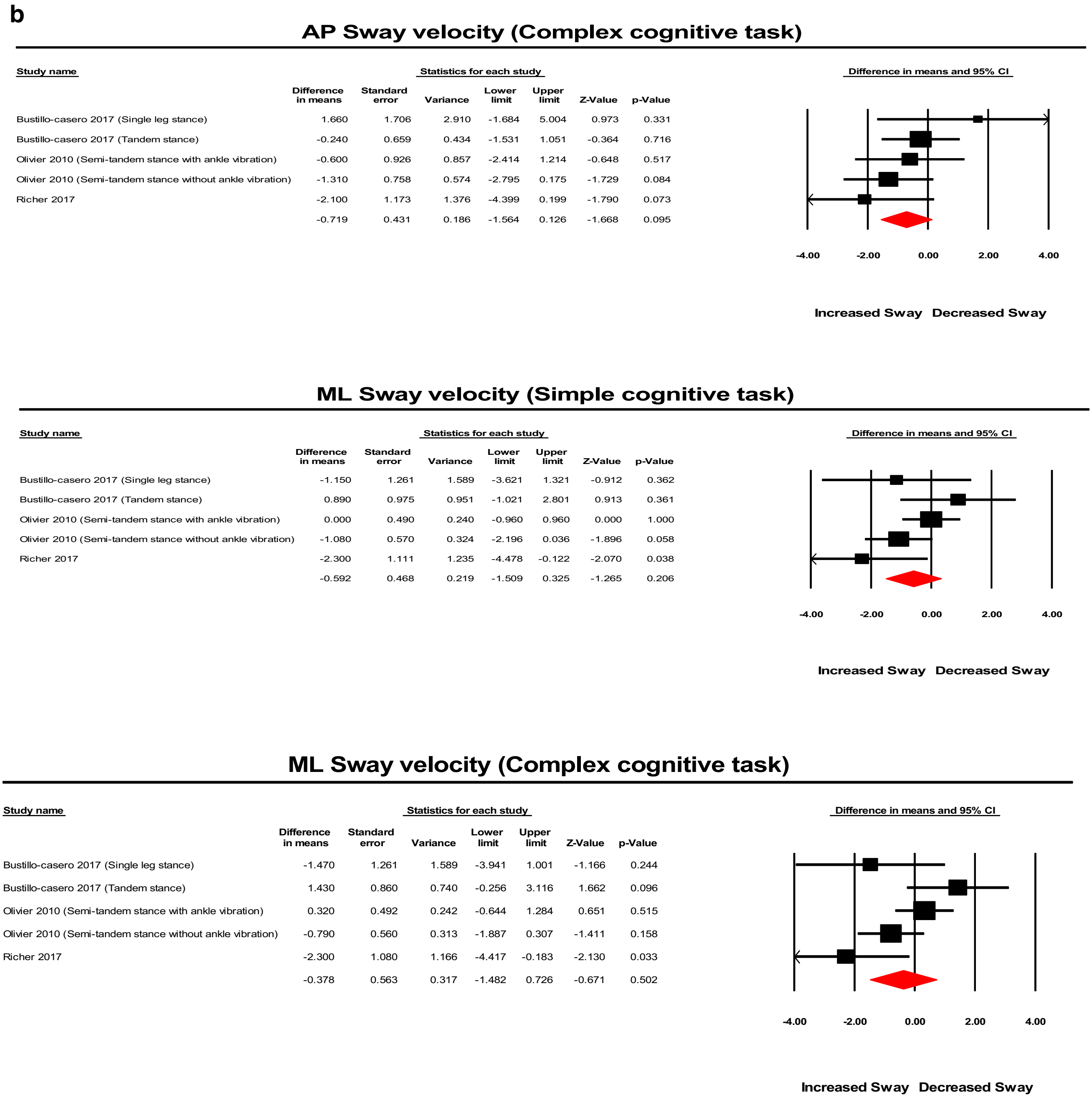
Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	-14.760	50.879	2588.625	-114.480	84.960	-0.290	0.772
Bustillo-casero 2017 (Tandem stance)	6.690	30.821	949.964	-53.719	67.099	0.217	0.828
Richer 2017	214.000	41.579	1728.840	132.506	295.494	5.147	0.000
Vuillerme and Vincent 2006	93.000	32.164	1034.538	29.959	156.041	2.891	0.004
	75.418	48.074	2311.069	-18.804	169.641	1.569	0.117

AP Sway velocity (Simple cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	0.580	1.739	3.022	-2.827	3.987	0.334	0.739
Bustillo-casero 2017 (Tandem stance)	-0.360	0.842	0.708	-2.009	1.289	-0.428	0.669
Olivier 2010 (Semi-tandem stance with ankle vibration)	-0.960	0.926	0.857	-2.774	0.854	-1.037	0.300
Olivier 2010 (Semi-tandem stance without ankle vibration)	-1.550	0.770	0.593	-3.060	-0.040	-2.012	0.044
Richer 2017	-2.100	1.196	1.431	-4.444	0.244	-1.756	0.079
	-1.042	0.435	0.189	-1.894	-0.190	-2.397	0.017

Fig. 3 **a–e** Forest plots showing the effect of simple and complex cognitive tasks on dual task postural stability during challenging postural task (Standing with eyes closed, standing on foam surface, one leg stance, tandem stance, semi tandem stance with and without ankle vibration, standing with feet together) in healthy young adults. *AP* Antero-posterior; *ML* Mediolateral; *EO* Eyes opened; *EC* Eyes closed

be sufficiently difficult to exceed the neural resource limit and cause dual task interference in relatively easy postural condition in older adults (Boisgontier et al. 2013). This increased postural sway could also be explained based on the cross-domain resource competition hypothesis (Wollesen et al. 2016). According to this hypothesis, both maintenances of postural stability and cognitive task performance draw from a limited pool of cognitive resources for their control, potentially leading to a decrease in postural stability,



AP Sway velocity (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	1.660	1.706	2.910	-1.684	5.004	0.973	0.331
Bustillo-casero 2017 (Tandem stance)	-0.240	0.659	0.434	-1.531	1.051	-0.364	0.716
Olivier 2010 (Semi-tandem stance with ankle vibration)	-0.600	0.926	0.857	-2.414	1.214	-0.648	0.517
Olivier 2010 (Semi-tandem stance without ankle vibration)	-1.310	0.758	0.574	-2.795	0.175	-1.729	0.084
Richer 2017	-2.100	1.173	1.376	-4.399	0.199	-1.790	0.073
	-0.719	0.431	0.186	-1.564	0.126	-1.668	0.095

ML Sway velocity (Simple cognitive task)

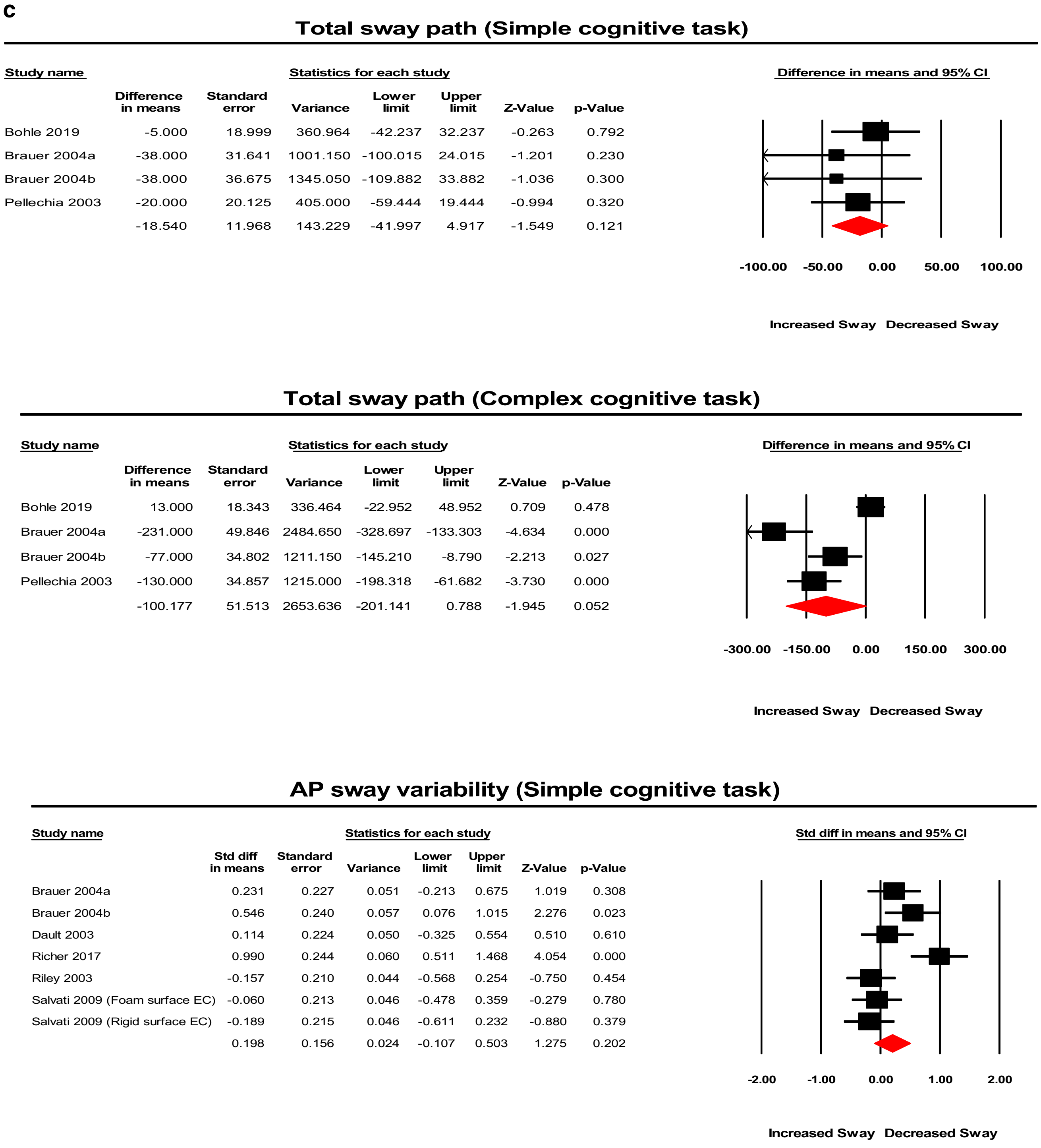
Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	-1.150	1.261	1.589	-3.621	1.321	-0.912	0.362
Bustillo-casero 2017 (Tandem stance)	0.890	0.975	0.951	-1.021	2.801	0.913	0.361
Olivier 2010 (Semi-tandem stance with ankle vibration)	0.000	0.490	0.240	-0.960	0.960	0.000	1.000
Olivier 2010 (Semi-tandem stance without ankle vibration)	-1.080	0.570	0.324	-2.196	0.036	-1.896	0.058
Richer 2017	-2.300	1.111	1.235	-4.478	-0.122	-2.070	0.038
	-0.592	0.468	0.219	-1.509	0.325	-1.265	0.206

ML Sway velocity (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bustillo-casero 2017 (Single leg stance)	-1.470	1.261	1.589	-3.941	1.001	-1.166	0.244
Bustillo-casero 2017 (Tandem stance)	1.430	0.860	0.740	-0.256	3.116	1.662	0.096
Olivier 2010 (Semi-tandem stance with ankle vibration)	0.320	0.492	0.242	-0.644	1.284	0.651	0.515
Olivier 2010 (Semi-tandem stance without ankle vibration)	-0.790	0.560	0.313	-1.887	0.307	-1.411	0.158
Richer 2017	-2.300	1.080	1.166	-4.417	-0.183	-2.130	0.033
	-0.378	0.563	0.317	-1.482	0.726	-0.671	0.502

Fig. 3 (continued)

cognitive task performance, or both, when the two tasks are carried out simultaneously. Older individuals have reduced peripheral sensibility in the visual, vestibular, and proprioceptive systems making them more reliant on attentional resources for balance control (Boisgontier et al. 2012; Glasser and Campbell 1998; Marsh and Geel 2000; Rosenhall 1973; Teasdale et al. 1993). Thus, even the simple act of maintaining quiet stance in older adults may not be automatic and performing it simultaneously with the cognitive task may limit the amount of available attentional resources for balance control leading to increased sway (Takakusaki 2017). With increasing balance challenge, most of the studies found increased sway (decreased postural stability) during dual tasking using both simple and complex cognitive tasks. This further support the cross domain-resource competition hypothesis. Since attentional requirement for balance control increases with increasing balance challenge (Lajoie et al. 1993), older adults may be unable to combine



Total sway path (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bohle 2019	-5.000	18.999	360.964	-42.237	32.237	-0.263	0.792
Brauer 2004a	-38.000	31.641	1001.150	-100.015	24.015	-1.201	0.230
Brauer 2004b	-38.000	36.675	1345.050	-109.882	33.882	-1.036	0.300
Pellechia 2003	-20.000	20.125	405.000	-59.444	19.444	-0.994	0.320
	-18.540	11.968	143.229	-41.997	4.917	-1.549	0.121

Total sway path (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bohle 2019	13.000	18.343	336.464	-22.952	48.952	0.709	0.478
Brauer 2004a	-231.000	49.846	2484.650	-328.697	-133.303	-4.634	0.000
Brauer 2004b	-77.000	34.802	1211.150	-145.210	-8.790	-2.213	0.027
Pellechia 2003	-130.000	34.857	1215.000	-198.318	-61.682	-3.730	0.000
	-100.177	51.513	2653.636	-201.141	0.788	-1.945	0.052

AP sway variability (Simple cognitive task)

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	0.231	0.227	0.051	-0.213	0.675	1.019	0.308
Brauer 2004b	0.546	0.240	0.057	0.076	1.015	2.276	0.023
Dault 2003	0.114	0.224	0.050	-0.325	0.554	0.510	0.610
Richer 2017	0.990	0.244	0.060	0.511	1.468	4.054	0.000
Riley 2003	-0.157	0.210	0.044	-0.568	0.254	-0.750	0.454
Salvati 2009 (Foam surface EC)	-0.060	0.213	0.046	-0.478	0.359	-0.279	0.780
Salvati 2009 (Rigid surface EC)	-0.189	0.215	0.046	-0.611	0.232	-0.880	0.379
	0.198	0.156	0.024	-0.107	0.503	1.275	0.202

Fig. 3 (continued)

the act of maintaining a difficult postural position with the performance of even a simple cognitive task without losing their balance. However, just like in the case of healthy young adults, a mixed effect (decreased sway area and increased sway velocity) during dual tasking while maintaining a difficult balance task in healthy old adults was reported in one of the included studies (Lajoie et al. 2017). This may imply that older adults also tend to prioritize either postural or cognitive task during dual-tasking depending on the level of threat to their stability and safety (Shumway-Cook et al. 1997), and that their performance will be influenced by their prioritization of postural control or cognition, in the context

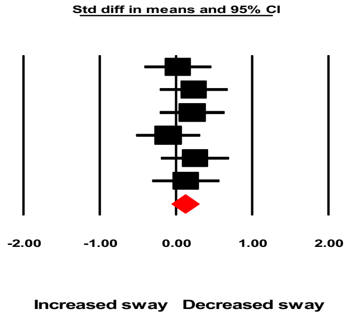
d

AP sway variability (Complex cognitive task)

Study name	Statistics for each study						
	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	0.210	0.226	0.051	-0.233	0.653	0.927	0.354
Brauer 2004b	0.546	0.240	0.057	0.076	1.015	2.276	0.023
Dault 2003	0.228	0.226	0.051	-0.216	0.672	1.005	0.315
Richer 2017	1.233	0.265	0.070	0.713	1.753	4.646	0.000
Riley 2003	0.149	0.210	0.044	-0.262	0.560	0.710	0.477
Salvati 2009 (Foam surface EC)	0.468	0.225	0.050	0.028	0.908	2.085	0.037
Salvati 2009 (Rigid surface EC)	0.013	0.213	0.045	-0.405	0.431	0.060	0.952
	0.387	0.141	0.020	0.110	0.664	2.736	0.006

ML sway variability (Simple cognitive task)

Study name	Statistics for each study						
	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	0.024	0.224	0.050	-0.414	0.463	0.109	0.913
Brauer 2004b	0.232	0.227	0.051	-0.212	0.677	1.025	0.305
Salvati 2009 (Standing on foam surface EC)	0.213	0.216	0.046	-0.210	0.635	0.987	0.324
Salvati 2009 (Standing on Rigid surface EC)	-0.104	0.214	0.046	-0.523	0.315	-0.485	0.628
Riley 2005a	0.250	0.227	0.052	-0.195	0.695	1.101	0.271
Riley 2005b	0.128	0.225	0.050	-0.312	0.568	0.570	0.568
	0.120	0.091	0.008	-0.057	0.298	1.331	0.183



ML sway variability (Complex cognitive task)

Study name	Statistics for each study						
	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	-0.644	0.246	0.060	-1.126	-0.162	-2.621	0.009
Brauer 2004b	0.047	0.224	0.050	-0.392	0.485	0.210	0.834
Salvati 2009 (Standing on foam surface EC)	0.269	0.217	0.047	-0.156	0.694	1.240	0.215
Salvati 2009 (Standing on Rigid surface EC)	0.106	0.214	0.046	-0.313	0.525	0.496	0.620
Riley 2005a	0.256	0.227	0.052	-0.189	0.701	1.127	0.260
Riley 2005b	0.256	0.227	0.052	-0.189	0.701	1.127	0.260
	0.059	0.134	0.018	-0.204	0.322	0.439	0.661

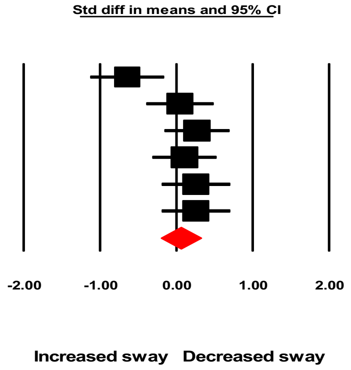


Fig. 3 (continued)

of their postural control ability or postural control reserve (Yogev-Seligmann et al. 2012).

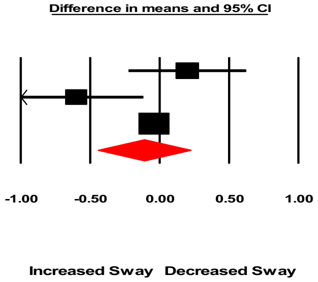
Conclusion

The results of this review strongly suggest a lack of qualitative interaction (i.e., where complex cognitive task produced effect in a different direction compared to the simple cognitive task) between cognitive task complexity and dual-task postural stability. Thus, the use of cognitive tasks of varying complexity may not explain why individual dual-task studies

e

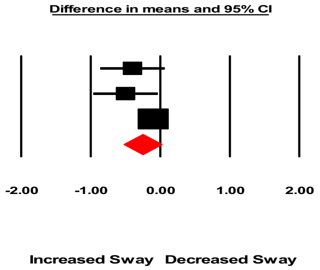
AP sway frequency (Simple cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	0.200	0.216	0.047	-0.223	0.623	0.927	0.354
Brauer 2004b	-0.600	0.246	0.061	-1.082	-0.118	-2.439	0.015
Vuillerme and Vincent 2006	-0.040	0.029	0.001	-0.097	0.017	-1.369	0.171
	-0.110	0.171	0.029	-0.444	0.224	-0.645	0.519



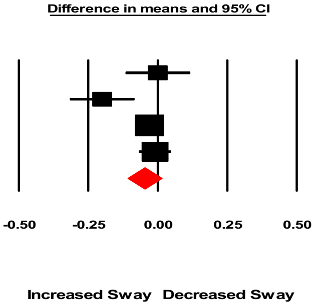
AP sway frequency (Complex cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	-0.400	0.236	0.056	-0.862	0.062	-1.698	0.090
Brauer 2004b	-0.500	0.236	0.056	-0.962	-0.038	-2.122	0.034
Vuillerme and Vincent 2006	-0.100	0.027	0.001	-0.154	-0.046	-3.661	0.000
	-0.253	0.140	0.019	-0.526	0.021	-1.810	0.070



ML sway frequency (Simple cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	0.000	0.059	0.004	-0.116	0.116	0.000	1.000
Brauer 2004b	-0.200	0.059	0.004	-0.316	-0.084	-3.381	0.001
Richer 2017	-0.030	0.018	0.000	-0.065	0.005	-1.667	0.096
Vuillerme and Vincent 2006	-0.010	0.029	0.001	-0.067	0.047	-0.342	0.732
	-0.047	0.031	0.001	-0.108	0.014	-1.516	0.130



ML sway frequency (Complex cognitive task)

Study name	Statistics for each study						
	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brauer 2004a	-0.100	0.059	0.004	-0.216	0.016	-1.690	0.091
Brauer 2004b	-0.200	0.097	0.010	-0.391	-0.009	-2.052	0.040
Richer 2017	-0.090	0.020	0.000	-0.130	-0.050	-4.434	0.000
Vuillerme and Vincent 2006	-0.040	0.031	0.001	-0.100	0.020	-1.311	0.190
	-0.080	0.020	0.000	-0.118	-0.041	-4.073	0.000

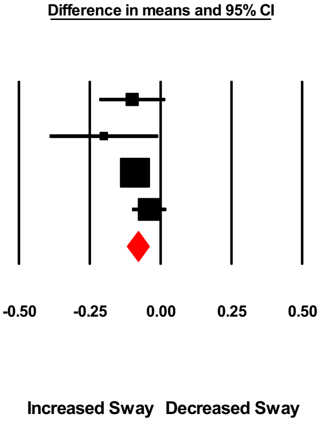
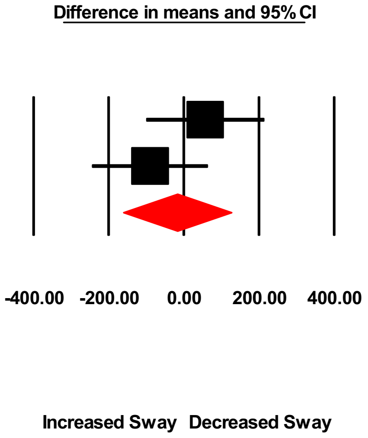


Fig. 3 (continued)

Sway area (Simple cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bourlon 2014	57.000	79.773	6363.700	-99.352	213.352	0.715	0.475
Neghaban 2017	-90.000	78.421	6149.864	-243.702	63.702	-1.148	0.251
	-17.227	73.496	5401.721	-161.278	126.823	-0.234	0.815



Sway area (Complex cognitive task)

Study name	Difference in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bourlon 2014	173.000	79.224	6276.433	17.724	328.276	2.184	0.029
Neghaban 2017	-101.000	74.664	5574.682	-247.338	45.338	-1.353	0.176
	34.719	136.994	18767.360	-233.784	303.223	0.253	0.800

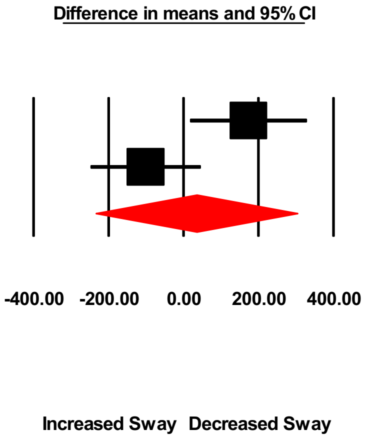


Fig. 4 Forest plots showing the effect of simple and complex cognitive tasks on postural stability during dual tasking in quiet standing in stroke patients

found varied effects of increased or decreased postural stability. Critical factors that may influence this shift in effect in the healthy population are age and postural task challenge. While maintaining a quiet stance, dual tasking improves postural stability in healthy young adults. In contrast, dual tasking in the same position reduced postural stability in healthy older adults. This implies that maintaining quiet standing in healthy young adults is automatic process regulated by brainstem and spinal cord neural circuits but with advancing age, this process becomes attention-demanding and thus requires cognitive resources (higher cortical functions). Contrarily, both young and older adults experienced increased sway during dual tasking in a more challenging postural position indicating the non-automaticity of postural control in these positions regardless of age. Further studies are needed to draw conclusions for clinical populations.

Limitations

The findings of this study should be interpreted in the context of the following limitations. Separate meta-analyses were conducted for the different postural sway measures. However, both the number and the studies pooled for each sway measure were not necessarily the same. This may affect the outcome of the analysis for each individual postural sway measure. Our analysis of dual tasking using challenging balance tasks also involved postural tasks which varied in their level of difficulty and may thus be affected differently by dual tasking. It should also be noted that the studies included in the study used different types of cognitive tasks and while some studies used tasks requiring verbal articulation of cognitive response during dual-tasking, others did not. Finally, our finding on older adults is based on the narrative synthesis of the result of the included studies.

Direction for future research

Since this review has found that cognitive task complexity does not account for the inconsistent effect of dual-tasking on postural stability, we suggest further dual-task studies including systematic reviews should investigate and clarify the effect of other methodological factors. An important factor suggested to contribute to inconsistent effects of dual tasking on postural stability is the use of cognitive tasks requiring vocal articulation of response (Riley et al. 2003). Thus, further studies are needed to investigate and clarify the exact effect of verbal articulation of cognitive response on dual task postural stability. Moreover, testing the effect of giving differentiated instruction to participants about the task they should prioritize during dual tasking may help to further explain the exact interaction between posture and cognition in dual task situations (Mitra and Fraizer 2004). Reporting the changes in cognitive performance between single and dual-tasks measurements may also reveal any trade-off between postural and cognitive task performance during dual tasking and enable better interpretation of results (Huxhold et al. 2006). In addition, the reliability of the postural outcome measures should be considered while interpreting findings of dual task posture studies. Finally, the use of non-linear analysis of posture may complement traditional posturography and provide further explanation on the effect of dual tasking on postural stability viz-a-viz the mechanism involved (Bernard-Demanze et al. 2009).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00221-021-06299-y.

Author contributions ATS conceptualization, methodology, formal analysis, data curation, writing-original draft preparation. SJ conceptualization, methodology, writing-review and editing. KDH conceptualization, methodology, writing-review and editing.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials All data generated or analyzed during this study is available and can be provided if required.

Declarations

Conflict of interest All the authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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