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The acute effects of mental fatigue on balance performance in healthy young and older adults – A systematic review and meta-analysis

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ABSTRACT

Cognitive resources contribute to balance control. There is evidence that mental fatigue reduces cognitive resources and impairs balance performance, particularly in older adults and when balance tasks are complex, for example when trying to walk or stand while concurrently performing a secondary cognitive task.

We conducted a systematic literature search in PubMed (MEDLINE), Web of Science and Google Scholar to identify eligible studies and performed a random effects meta-analysis to quantify the effects of experimentally induced mental fatigue on balance performance in healthy adults. Subgroup analyses were computed for age (healthy young vs. healthy older adults) and balance task complexity (balance tasks with high complexity vs. balance tasks with low complexity) to examine the moderating effects of these factors on fatigue-mediated balance performance.

We identified 7 eligible studies with 9 study groups and 206 participants. Analysis revealed that performing a prolonged cognitive task had a small but significant effect (*SMDwm* = −0.38) on subsequent balance performance in healthy young and older adults. However, age- and task-related differences in balance responses to fatigue could not be confirmed statistically.

Overall, aggregation of the available literature indicates that mental fatigue generally reduces balance in healthy adults. However, interactions between cognitive resource reduction, aging and balance task complexity remain elusive.

1. Introduction

Balance is a skill-related component of physical fitness that involves controlling the body's center of mass over the base of support to maintain equilibrium and prevent falls (Caspersen et al., 1985; Winter, 1995). Rather than being a single motor ability, balance is multidimensional and highly task-specific so that, when it is practiced, there is little transfer from a practiced to a not-practiced balance task (Giboin et al., 2015). According to Shumway-Cook and Woollacott (2016), balance can be classified as static steady-state balance, dynamic steady-state balance, reactive balance, and proactive balance. While static steady-state balance refers to the maintenance of equilibrium characterized by no or little change of acceleration of the center of mass, such as sitting or standing, dynamic steady-state balance refers to the maintenance of equilibrium during locomotion. Furthermore, balance is described as reactive when an effort is made to stabilize the body's center of mass over the base of support in response to unexpected perturbations, and as proactive, when anticipatory and self-initiated postural adjustments are made. Given the relative independence of these balance components, test batteries have been developed to

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comprehensively assess balance performance under various conditions (Berg et al., 1992). These test batteries have been shown to predict functional outcomes, such as falls rate and/or risk, for healthy adults as well as for patient populations (Leddy et al., 2011; Maeda et al., 2009; Magnani et al., 2020).

For decades, researchers have assumed that balance control is automatic and requires no or only little cognitive resources (Dietz et al., 1991; Nashner, 1976; Takakusaki et al., 2004). More recently however, studies employing cognitive-postural dual-tasks (e.g., balancing while counting backwards) and sensory manipulations (e.g., balancing with eyes closed) have demonstrated notable cognitive involvement in static and dynamic balance control (Granacher et al., 2011; Karim et al., 2013; Papegaaij et al., 2017; St George et al., 2021; Stelzel et al., 2017; Teo et al., 2018). For example, Papegaaij et al. (2017) showed that brain activity increased in both young and older adults when a cognitive dual-task was performed during a static balance simulation task. Likewise, Teo et al. (2018) demonstrated increased cortical activation in young and older adults when visual and/or proprioceptive feedback was manipulated during stance and found that the magnitude of increase was related to the sensory complexity of the balance task. It has been postulated that increased cortical activity may indicate functional compensation in the form of increased attentional demands to prevent balance loss in potentially fall-threatening situations (Lajoie et al., 1993; Papegaaij et al., 2014). Conversely, balance performance might be compromised when cognitive resources are limited. Indeed, older adults, who experience an overall age-related cognitive decline, exhibit greater reductions in dual-task balance performance than healthy young adults (Behrens et al., 2017) and individuals with mild cognitive impairment are less stable during quiet stance and walk at slower gait speeds than their cognitively fitter counterparts, particularly when they are challenged cognitively (Deschamps et al., 2014; Muir et al., 2012).

In addition to undergoing slow neurodegenerative or general age-related decline, cognitive resources can also degrade rapidly in response to different external or internal conditions and environments such as fatigue. Since a large part of the general population, and older adults in particular, report tiredness and fatigue (Doris et al., 2010), a more comprehensive understanding of balance control should therefore also consider acute depletion of physical or mental resources. Regarding physical fatigue, it is well-established that prolonged (e.g., walking for a long distance) or short bouts of high-intensity muscle actions (e.g., running to catch a bus) impairs static and dynamic balance performance, independent of age (Papa et al., 2015; Santos et al., 2019). However, emerging evidence suggests that mental fatigue, which has been defined as a psychobiological state caused by prolonged periods of demanding cognitive activity characterized by changes in mood, motivation and task performance (Boksem et al., 2005; Boksem and Tops, 2008; Marcora et al., 2009), may also deteriorate balance performance (Behrens et al., 2017). However, no systematic review and meta-analysis has yet synthesized the effects of mental fatigue on proxies of balance in healthy adults from different age groups. Although a recent narrative review by Grobe et al. (2017) claims to have examined the effects of mental fatigue on static and dynamic balance in older adults, the article did not include studies that employed mental fatigue interventions. A recent systematic review by Santos et al. (2019) analyzed the effects of both physical and mental fatigue on older adults' gait. The authors identified only one study that employed a mental fatigue protocol and consequently were unable to provide a comprehensive review of the effects of this type of intervention. Moreover, no study has investigated how moderating variables, such as age and balance task complexity, may impact the mental fatigue response. Such knowledge, however, is necessary to make meaningful inferences about situations or conditions that pose a particular threat to balance and the populations who are most susceptible to falls.

Against this background, the aim of this systematic review and meta-analysis was to quantify the acute effects of mental fatigue induced by prolonged cognitive activity on balance performance in adults without any pre-existing medical conditions. Given the general age-related cognitive decline and its potential impact on balance control, we also wanted to test if young vs. old age is a moderator with respect to the outcome measures. Since balance has been shown to decrease after prolonged cognitive activity, particularly under complex conditions (Behrens et al., 2017) we also wanted to investigate if balance tasks with high complexity (i.e., cognitive-postural dual tasks or balance tasks with manipulated sensory feedback) are more affected by mental fatigue than balance tasks with low complexity (i.e., single task balance conditions with non-manipulated sensory feedback). Based on existing systematic reviews and/or meta-analyses that report physical performance declines after a mentally fatiguing task (Brown et al., 2020; Habay et al., 2021; McMorris et al., 2018; Van Cutsem et al., 2017), we hypothesized that mental fatigue would generally decrease balance performance. We also expected to find greater effects of fatigue in more complex compared to less complex balance tasks as well as in older compared to younger adults (Behrens et al., 2017).

2. Methods

Our systematic review follows the PRISMA framework designed to provide comparability, research integrity, and transparency. We considered randomized controlled trials (RCTs) as well as non-randomized controlled trials (nRCTs) with crossover and parallel group designs for inclusion in our analysis. In accordance with the criteria specified in the Cochrane Handbook for Systematic Reviews of Interventions, data from crossover trials was treated as if it was derived from separate parallel groups (Higgins et al., 2019).

2.1. Literature search

We performed a computerized systematic literature search in PubMed, Web of Science and Google Scholar up to June 2021. Our Boolean search strategy used a combination of the operators 'AND', 'OR', 'NOT' to produce the following syntax ("mental fatigue" OR "cognitive fatigue" OR "mental exertion" OR "cognitive exertion" OR "mental exhaustion" OR "cognitive exhaustion" OR "ego depletion") AND (adult[mesh] OR "healthy adults" OR "older adults" OR "young adults") AND ("postural control" OR balance OR gait OR walk OR "postural stability") NOT child NOT infant NOT athlete. The 'NOT' operator was used to define exclusion terms and reduce the number of search results. The syntax was adapted for the Web of Science and Google Scholar search. The respective search syntaxes can be found in the supplement of this article. Only full-text articles in English were considered for inclusion. We also performed a grey literature search and screened the reference lists of already published review articles for potentially relevant studies.

2.2. Eligibility criteria

The PICOS (Population, Intervention, Comparator, Outcome, Study Design) approach was used to identify studies eligible for inclusion (Moher et al., 2009). The following inclusion criteria were defined a priori (a) population: young adults aged 18 to 30 years as well as older adults aged ≥60 years without any history of neurological, orthopedic, or cardiovascular health conditions (b) intervention: prolonged and/or exhaustive mental activity designed to induce mental fatigue; (b) comparator: passive control groups or conditions; (c) outcome: at least one measure of balance (i.e. static steady-state balance, dynamic steady-state balance, reactive balance, proactive balance) assessed through an easy-to-administer clinical (e.g., time during single-leg stance) or biomechanical (e.g., center of pressure displacements during single-leg stance) test method; (d) study design: within- and between-subject randomized controlled trials as well as non-randomized controlled trials with pre- and post-fatigue measures. Studies were excluded if they only investigated children, patients, or people with diseases; if they investigated chronic fatigue, fatigability or fatigue in the physical domain; if they did not include a group of healthy young or older adults as comparator or if they did not quantify mental fatigue following the intervention.

2.3. Data extraction/coding of studies

We merged the results from the queried databases and subsequently removed all duplicates (Fig. 1). Two researchers (MB, MA) then independently screened for titles (first iteration) and abstracts (second iteration) of the listed articles. If an article was identified as being potentially eligible for inclusion, we obtained the full-text and extracted the data relevant for our review into a standardized excel form, comparing if the studies fit our criteria. Consensus of the reviewers was checked at each stage (i.e., title, abstract, full text). If no consensus was achieved between the two reviewers (MB, MA), a third reviewer (UG) was contacted to achieve agreement. If relevant data was not reported in the article, we contacted the authors for missing data. Extracted study items included the research question(s), details regarding the study cohort and the comparator (sample size, age, sex, anthropometric characteristics, inclusion/exclusion criteria, physical activity status), characteristics of the fatigue task (protocol, duration) and the assessment of fatigue, i.e., a specified endpoint. We also extracted information regarding the type of balance assessment and the reported effects of mental fatigue on the respective outcome parameters.

For each study, we first determined which balance component was assessed. In accordance with the balance classification of Shumway-Cook and Woollacott (2016), we included studies that measured static balance (i.e., maintaining a steady position while standing), dynamic balance (i.e., maintaining a steady position while walking), proactive balance (i.e., anticipatory and self-initiated changes in posture) and reactive balance (i.e., balance recovery). In case a study reported more than one balance component, we only considered the test balance component that most accurately reflects health, functional capacity, and risk of falls. Consequently, dynamic balance was ranked highest (e.g., 10-m walk test), followed by reactive balance (e.g., excursions in response to a perturbation impulse), proactive balance (e.g., Functional Reach Test), and lastly static balance (excursions of center of pressure displacements during quiet stance). However, if a study used a balance test battery (e.g., Berg Balance Scale), we chose this test instrument over any of the individual balance components, because test batteries consist of several balance tasks that include different balance components and thus represent a comprehensive balance assessment (Berg et al., 1992). As a next step, we checked if a study assessed balance in different postural or standing positions. If this was the case, we selected the position with the highest postural demand (e.g., reduced base of support) in case one study assessed balance for different postural positions For example, single leg stance was chosen over bilateral parallel stance. This was done because our study population consisted of healthy people. Of note, balance tests with low postural demands (i.e., bipedal stance) have

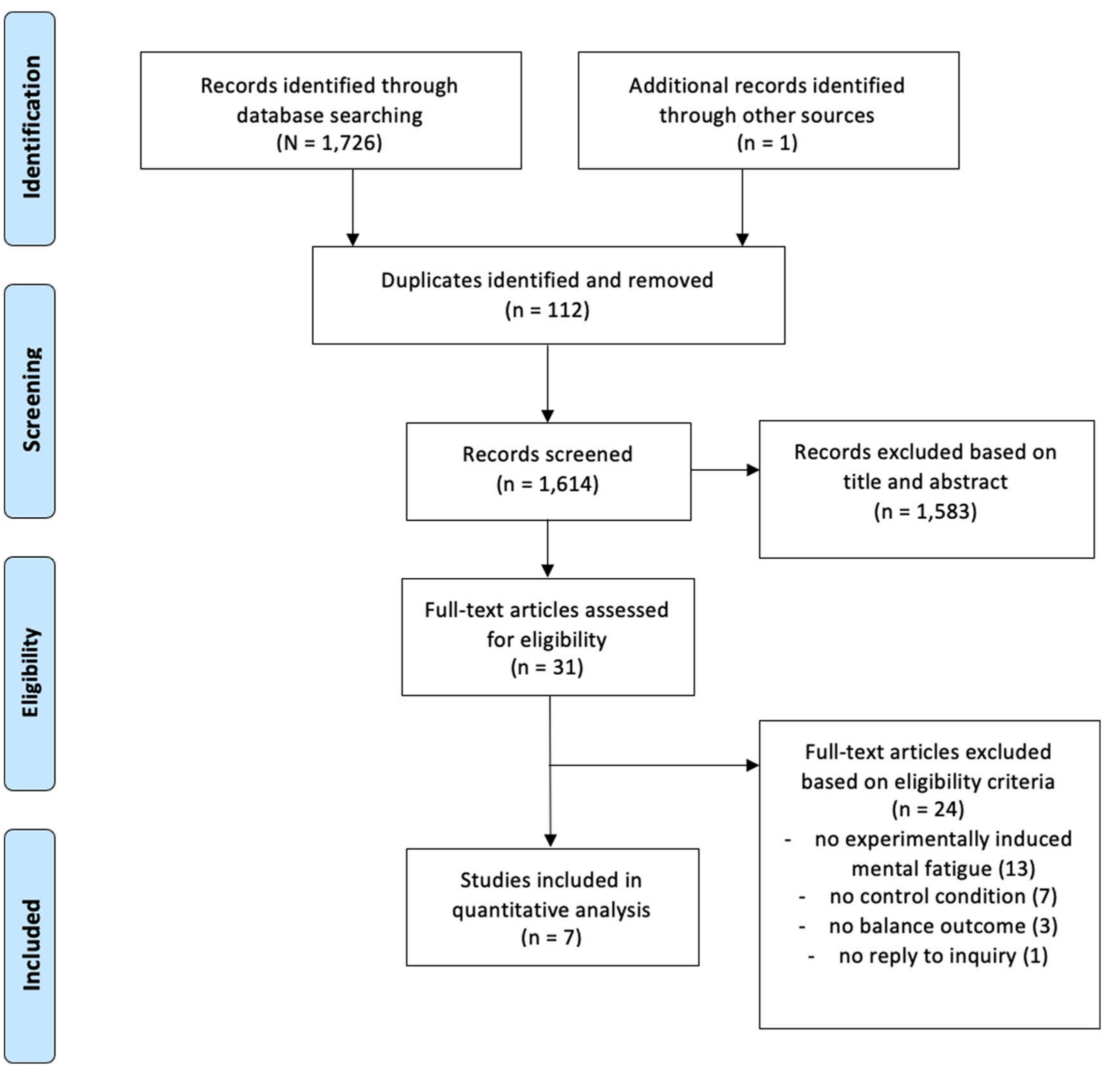

Fig. 1. Flow chart illustrating the selection process of the systematic literature search.

been shown to produce ceiling effects in young healthy adults (Era et al., 2006). Moreover, we checked if a study assessed balance while performing secondary cognitive tasks or while manipulating sensory feedback. This was done because these conditions have been associated with increased cortical activity during balance performance (Karim et al., 2013; St George et al., 2021), which is likely to cause greater interactions with mental fatigue (Behrens et al., 2017; Varas-Diaz et al., 2020). Consequently, if a study assessed balance under cognitive-postural dual-task conditions or manipulated sensory feedback it was classified as balance with high task complexity. In contrast, studies that did not use sensory manipulation or cognitive-postural dual-tasks were classified as balance tests with low task complexity. Lastly, when multiple outcomes were reported for a single balance test or component (e.g., walking speed and stride length), a variable that contained information about both spatial and temporal characteristics (i.e., walking speed or CoP velocity) was selected for inclusion in the analysis. Based on this decision tree, the highest priority was given to CoP velocity measured in single leg stance under dual-task conditions in the category static steady-state balance. As a preferred proxy for dynamic steady-state balance, gait speed measured under dual-task conditions was used. The Timed Up-and-Go test with a cognitive dual-task was preferably selected as a proxy for proactive balance, and finally for reactive balance, we chose CoP velocity following a perturbation impulse under dual-task conditions. If a study used other tests, we decided to include those tests in our quantitative analyses that were most similar in terms of their temporal-spatial characteristics (e.g., tandem walking) to the ones described above.

2.4. Quality assessment and statistical analyses

To reduce the risk of misinterpretation of evidence and improve transparency with regards to the generalizability of results, two authors (MA, MB) independently assessed the risk of bias of the included studies using a quality appraisal tool developed by Galna et al. (2009). The tool evaluates both, internal and external validity, replicability and contains questions regarding potential confounding factors (Table 1). Individual items are scored between 0 and 1, with some categories allowing for half points. A score of 1 was assigned for an item if the information relating to that item was completely available, a score of 0.5 was provided if the description was lacking clarity or details, and a score of 0 was provided if no information were available in the article at all. The quality appraisal tool has been used in other systematic reviews and meta-analyses (Barrett et al., 2010; Dos Santos et al., 2019; Obst et al., 2018).

Publication bias was assessed using small sample bias methods. Accordingly, funnel plots were computed and checked for asymmetry. Asymmetrical funnel plots indicate that publication bias may be present, because small studies may have been published with larger effect sizes while small studies without a significant, large effect are missing (Egger et al., 1997). Egger's test was used as an additional method to check for publication bias.

Table 1
Methodological quality of the included studies.

Question	Scoring criteria	Behrens et al. (2017)	Boolani et al. (2020)	Hachard et al. (2020)	Morris and Christie (2020)	Tassignon et al. (2020)	Varas-Diaz et al. (2020)	Verschueren et al. (2020)
Research aim or question clearly stated	1–Yes; 0.5–yes, lacking detail or clarity; 0 – no	1	1	1	1	1	1	1
Participant characteristics 1–yes; 0.5–yes, lacking detail or clarity; 0 – no	N	1	1	1	1	1	1	1
	Age	1	1	1	1	1	1	1
	Sex	1	1	1	1	1	0	1
	Body height	1	1	1	1	1	1	1
	Sub-total	1	1	1	1	1	0.8	1
Recruitment and sampling methods described	1–Yes; 0.5–yes, lacking detail or clarity; 0 – no	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Inclusion and exclusion criteria detailed	1–Yes; 0.5–yes, lacking detail or clarity; 0 – no	1	1	1	1	1	1	1
Key outcome variables clearly described	1–Yes; 0.5–yes, lacking detail or clarity; 0 – no	1	1	1	1	1	1	1
Adequate methodology to repeat study 1–yes; 0.5–yes, lacking detail or clarity; 0 – no	Participants	1	1	1	1	1	0.5	1
	Equipment	1	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1	1
	Data processing	1	1	1	1	1	1	1
	Statistical analysis	1	1	1	1	1	1	1
	Sub-total	1	1	1	1	1	0.9	0.9
Methodology able to answer research question 1–yes; 0.5–yes, lacking detail or clarity; 0 – no	Participants	1	1	1	1	1	1	1
	Equipment	1	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1	1
	Data processing	1	1	1	1	1	1	1
	Statistical analysis	1	1	1	1	1	1	1
	Sub-total	1	1	1	1	1	1	1
Reliability of methodology stated	1–Yes; 0–no	0	0	0	0	0	0	0
Internal validity of the method stated	1–Yes; 0–no	0	0	0	0	0	0	0
Research questions answered adequately in the discussion	1–Yes; 0–no	1	1	1	1	1	1	1
Key findings supported by the results	1–Yes; 0–no	1	1	1	1	1	1	1
Key findings logically interpreted and supported by references	1–Yes; 0–no	1	1	1	1	1	1	1
Clinical implications stated	1–Yes; 0.5–yes, lacking detail or clarity; 0 – no	1	1	0	0	1	1	1

Weighted between-study standardized mean differences (SMDs) were computed for pre-test and post-test values of each study according to the formula ($SMD = M1 - M2 / SD_{pooled}$), where M_1 stands for the mean pre/post-value of the intervention group, M_2 for the mean pre/post-value of the control group, and SD_{pooled} for the pooled standard deviation. Moreover, SMDs were adjusted for small sample sizes by using the following factor $[1 - 3 / (4N - 9)]$, with N representing the total sample size (Hedges & Olkin, 2014). Additionally, adjusted SMD values were calculated as the difference between pre-test SMD to post-test SMD (Durlak, 2009). Effect size values of $\leq$0.20 indicate trivial, 0.20–0.50 indicate small, 0.50–0.80 indicate medium, and $\geq$0.80 indicate large effects (Cohen, 1992).

Quantitative data synthesis for meta-analyses was computed in *R* using the *meta* and *dmetar* packages (Harrer et al., 2019b; Schwarzer, 2007). A random effects model was applied to weigh each included study according to the magnitude of its standard error and to calculate the weighted mean SMD (SMD_{wm}). Fatigue-related changes in balance performance can be represented by an increase (positive) or decrease (negative) in the respective outcome parameter (i.e., CoP path length vs. time). Therefore, any fatigue effects were presented as negative SMD_{wm} to improve readability. Independent subgroup meta-analyses were computed for age group (healthy young vs. healthy older adults) and balance task complexity (balance with high task complexity vs. balance with low task complexity) to examine the moderating effects of these factors on fatigue-mediated balance performance. For this purpose, SMD_{wm} for the different subgroups were first aggregated and then compared for differences using Cochran's *Q* test (Cochran, 1954). Since our study sample was smaller than the recommended number of 10 studies (Higgins et al., 2019), we did not perform a meta-regression to verify the influence of any variables of the mental fatigue protocols on balance performance. Between-study heterogeneity was assessed using I^2, which signifies the percentage of variability in the effect sizes not caused by sampling error. Low, moderate, and high heterogeneity correspond to I^2 outcomes of 25%, 50%, and 75%, respectively (Higgins et al., 2003). To check whether the between-study heterogeneity was affected by certain studies with extreme effect sizes, we additionally screened our study sample for outliers using the *find.outliers* function of the *dmetar* R-package data and performed an influence analysis based on the Leave-One-Out-method (Harrer et al., 2019a). Studies were classified as outliers when their 95% confidence interval (95% CI) lay outside the 95% confidence interval of the pooled effect. Forest plots were generated in R using the *meta* package. The level of significance was set at $p < 0.05$.

3. Results

3.1. Study characteristics

Using the search criteria presented above, a total of 1726 studies were identified in the databases as being potentially relevant to our analysis. Searching the grey literature and screening the reference lists of relevant studies and reviews, we identified 1 additional study. After removing 112 duplicates, we screened the titles and abstracts of 1614 studies of which 1583 studies were excluded. Of the remaining 31 full texts, 24 studies were excluded, leaving 7 studies to be included in the quantitative analysis. Fig. 1 shows a flow chart for schematic inclusion and exclusion of the studies. All but one study employed a within-subject crossover design (Varas-Diaz et al., 2020). In accordance with the Cochrane guidelines, both designs were included in the analysis (Higgins et al., 2019). Table 1 provides a summary of all included studies. A total of 206 adults participated in the included studies of which 135 participants performed a mental fatigue task. Two studies investigated both a group of healthy young and a group of healthy older adults (Behrens et al., 2017; Morris & Christie, 2020), so the analysis included a total 9 different experimental groups ranging between 11 and 16 participants. Four treatment groups consisted of healthy older adults aged 68.4 ± 4.2 years, while five groups consisted of healthy young adults aged 22.8 ± 1.4 years. Mean age of all participants was 42.1 ± 2.6 years.

3.2. Study quality and analysis of bias

All included studies adequately state the objectives of each study, describe the subject characteristics in detail and use an appropriate methodological approach to answer the research question. None of the included articles had a poor scientific quality, but only one study provides information on reliability and internal validity. In addition, only one of the seven articles explicitly states the clinical or practical benefit of the findings. In four studies, the practical implications are incomplete or completely missing (see Table 1). The funnel plots of effect sizes did not show considerable asymmetry (Fig. 2), which was also supported by Egger's test of intercept ($\beta_0 = -5.68$, 95% CI = −12.93–1.55, $t = -1.54$, $p = 0.17$). This suggests that the distribution of effect sizes was not biased with respect to selective publication of studies. The Leave-one-out analysis did not result in changes in the overall direction or significance of the result.

3.3. Mental fatigue interventions

All of the included studies used prolonged cognitive tasks to induce mental fatigue, but the type of tasks varied between studies: Behrens et al. (2017) as well as Varas-Diaz et al. (2020) had participants perform a stop-signal task for 90 and 60 min, respectively; Tassignon et al. (2020); Verschueren et al. (2020) used a 100% incongruent Stroop color word test; Morris and Christie (2020) asked participants to perform the Psychomotor Vigilance Task (PVT) for 20 min, and Hachard et al. (2020) used the AX-Continuous Performance Task (AX-CPT) for 90 min to induce fatigue. Boolani et al. (2020) had participants perform a sequence of different cognitive tasks for a total time of 33 min. More specifically, their tasks consisted of serial subtractions (−3 and −7) from a randomly selected number for 2 min each, followed by a 2-minute AX-Continuous Performance Task, a 16-minute Rapid Visual Input Processing Task (RVIP). Afterwards participants performed a combination of Rapid Finger Tapping Tasks, and the Trail-Making Test-A and -B for 11 min. All studies employed a time-matched control condition, in which participants watched a neutral nature documentary or rested in a neutral environment.

All articles assessed subjective feelings of mental fatigue or mental energy in the experiment. Questionnaires included the 30-point Profile of Mood Survey- Short Form (POMS-SF) (Behrens et al., 2017; Boolani et al., 2020), the National Aeronautics and Space Administration – Task Load Index (NASA-TLX) (Hachard et al., 2020; Tassignon et al., 2020; Varas-Diaz et al., 2020; Verschueren et al., 2020) and the Mental and Physical State and Trait Energy and Fatigue scale (Boolani et al., 2020). Morris and Christie (2020) asked participants to rate their subjective fatigue on a 10-point scale using the question ("How sleepy do you feel?"). Six out of seven studies reported that subjective ratings of mental fatigue increased after performing the cognitive tasks. Boolani et al. (2020) did not find changes in mental fatigue ratings after the cognitive task but report that participants indicated significant declines in energy and state mental energy. Behrens et al. (2017) as well as Varas-Diaz et al. (2020)additionally assessed heart-rate variability and noted changes associated with greater psychophysiological workload and decreased parasympathetic activity. With regard to cognitive task performance, Morris and Christie (2020) as well as Hachard et al. (2020) reported a significant decrease in young participants' reaction time over the course of the protocol, while Behrens et al. (2017) did not find any changes in SST reaction times. Task accuracy, that is the number or percentage of correct responses, was reduced in one study (Hachard et al., 2020), while others did not report any effects in response to a fatiguing mental task (Tassignon et al., 2020; Verschueren et al., 2020). Notably, Varas-Diaz et al. (2020) found lower task performance in serial subtractions after a fatiguing SST-protocol but no change in reaction

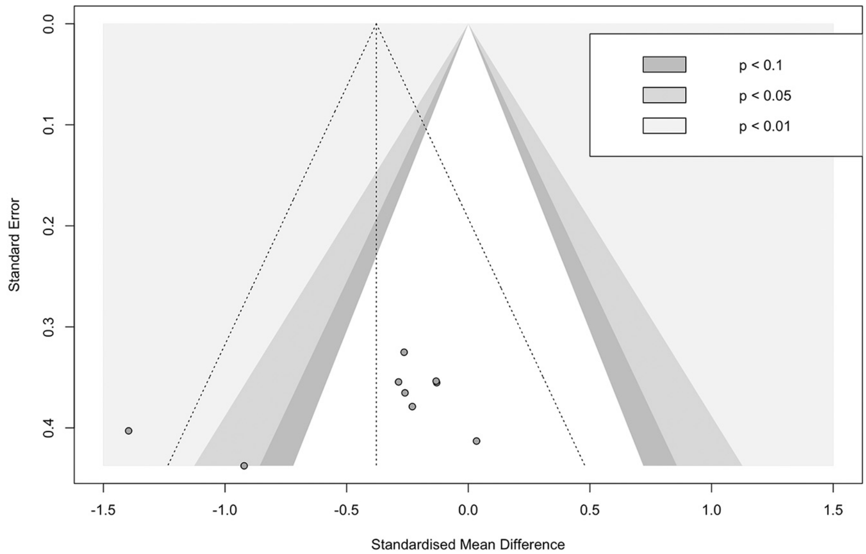

Fig. 2. Funnel plot of the effect sizes included in the meta-analysis.

times between task blocks. Verschueren et al. (2020) noticed improved task accuracy in the Eriksen-Flanker task after a fatiguing 90-minute Stroop task. One study did not assess cognitive task performance in their experiment (Boolani et al., 2020).

Five out of seven studies explicitly assessed test motivation before and after the mental fatigue intervention and none of them reported any changes in motivational scores. No study offered monetary incentives or other compensation for successfully completing the experiment. An overview of the applied fatigue protocols and the aims and results of the studies are presented in Table 2.

3.4. Effects of mental fatigue on balance performance

Three studies with four intervention groups included balance tasks with high complexity, while four studies with four intervention groups used balance tasks with low complexity. Four studies (four groups) and five studies (five groups) investigated the effects of mental fatigue on balance performance in old and young people, respectively. Eight out of nine study groups demonstrated balance decrements after participants performed a mentally fatiguing task. The pooled SMD_{wm} across all study was −0.38 (95% CI [−0.72, -0.04], $p = 0.03$). Overall, study heterogeneity was low ($I^2 = 23\%$).

3.5. Subgroup analyses

Using random effect models, we performed subgroup analyses for age (young vs. older adults) and balance task complexity (low vs. high task complexity) to elucidate the effects of these variables on the fatigue response. The analysis revealed higher SMD_{wm} for older ($SMD_{wm} = -0.62$; 95% CI [−1.61, 0.38]) compared to young adults ($SMD_{wm} = -0.22$; 95% CI [−0.37, -0.06]) but the test for subgroup differences was not significant ($Q = 1.6$, $df = 1$, $p = 0.20$), see Fig. 3. Subgroup analysis further revealed higher SMD_{wm} for balance tasks with high complexity ($SMD_{wm} = -0.49$; 95% CI [−1.40, 0.41]) compared to tasks with low complexity $SMD_{wm} = -0.28$; 95% CI [−0.70, 0.14]), but the results did not reach the level of statistical significance ($Q = 0.44$, $df = 1$, $p = 0.51$) see Fig. 4.

Study heterogeneity was low for young ($I^2 = 0\%$) and moderate for older ($I^2 = 62\%$) adults, while it was moderate for balance tasks with high complexity ($I^2 = 56\%$) and low for balance tasks with low task complexity ($I^2 = 0\%$).

4. Discussion

Given that a large part of the general population, and older individuals in particular, frequently experience feelings of fatigue and there appears to be an association between cognitive functioning and balance control, the purpose of this systematic meta-analytical review was to quantify the effects of experimentally induced mental fatigue on balance tasks with high and low complexity in healthy young and older adults. We found that performing a prolonged cognitive task had a small but significant effect ($SMD_{wm} = -0.38$) on the performance of subsequent balance tasks in healthy young and older adults. However, we could not confirm the existence of age- and task-related differences in balance responses to fatigue. Together, our results support the idea that mental fatigue produces small reductions in balance performance, irrespective of age and task difficulty.

4.1. Effects of mental fatigue on balance performance

Although this is the first attempt to synthesize the literature on mental fatigue and balance performance, several meta-analyses and systematic reviews have confirmed the negative effects of mental fatigue on other aspects of physical performance. For example, Giboin and Wolff (2019) recently showed that prolonged mental activity impairs endurance performance ($SMD_{wm} = -0.51$). Brown et al. (2020) reported small-to-medium effects ($SMD_{wm} = -0.38$) of mental fatigue on measures of muscular strength, power, endurance, and sport-specific motor performance but no effects on measures of anaerobic performance. Other meta-analyses confirmed the detrimental effects of mental fatigue on physical performance (Habay et al., 2021; McMorris et al., 2018), but also mentioned evidence of publication or reporting biases (Holgado et al., 2020). We show that experimentally induced mental fatigue reduces balance performance in healthy young and older adults and that the overall effect is small. Thus, our results confirm existing accounts of the detrimental effects of fatigue on physical performance.

Evidence also suggests that the mental fatigue response may be mediated by the type of physical task that is performed. For example, isolated muscle tasks appear to be more sensitive to mental fatigue than global tasks, such as cycling (Giboin & Wolff, 2019). It has been proposed that this effect may be linked to differences in automatic control, with isolated muscle tasks requiring greater attentional control (Giboin & Wolff, 2019). In this regard, early evidence from the balance literature suggested that dual-task balance performance might be more sensitive to mental fatigue than single-task balance (Behrens et al., 2017). Thus, we

Table 2
Studies examining the effects of mental fatigue on measures of static and dynamic balance in healthy young and older adults.

Study	Participants			Fatigue protocol			Balance task		Outcomes	
	N	Sex (F/M)	Age (years)	Task	Duration (min)	Control	Balance component/test	Task complexity	Balance performance	Measures of fatigue/cognitive performance
Behrens et al. (2017)	IG (16) CG (16)	10/6	Young (25 ± 1)	Stop-Signal Task	90	Nature documentary	Dynamic balance: 10 m walking	High (dual-task)	↓ −2.6% (walking speed)	↑ POMS fatigue ↓ wakefulness, mood, arousal ↔ reaction time of cognitive task, HRV
Behrens et al. (2017)	IG (16) CG (16)	8/8	Old (72 ± 4)	Stop-Signal Task	90	Nature documentary	Dynamic balance: 10 m DT walking	High (dual-task)	↓ −1.6% (walking speed)	↑ POMS fatigue ↓ wakefulness, mood (more nervous), arousal, cognitive performance ↔ reaction times of cognitive task, HRV
Boolani et al. (2020)	IG (11) CG (11)	7/4	Old (63 ± 5)	Serial subtractions, Continuous Performance Task, Rapid Visual Input Processing Task, Finger Tapping Task, Trail-Making Test A/B	30	Rest	Test battery: Berg Balance Scale	Low	↓ −2.7% (points)	↔ POMS fatigue, motivation to perform physical tasks, state physical energy and fatigue, and state mental fatigue ↓ POMS energy & state mental energy
Hachard et al. (2020)	IG (19) CG (19)	7/13	Young (22 ± 2)	Continuous Performance Task	90	Nature documentary	Static balance: Stable parallel bipedal stance	High (sensory manipulation: standing with eyes closed)	↓ +22.7% CoP velocity	↑ NASA-TLX mental, physical & temporal demand, effort, frustration, reaction times of cognitive task ↓ NASA-TLX performance, accuracy of cognitive task
Morris and Christie (2020)	IG (16) CG (16)	16/0	Old (73 ± 2)	Psychomotor Vigilance Task	20	Nature documentary	Reactive balance: Stable parallel bipedal stance with postural perturbations	Low	↓ +15% COP velocity	↑ subjective mental fatigue ↔ MFI (motivation), PSQI, reaction time of cognitive task
Morris and Christie (2020)	IG (16) CG (16)	16/0	Young (22 ± 1)	Psychomotor Vigilance Task	20	Nature documentary	Reactive balance: Stable parallel bipedal stance with postural perturbations	Low	↓ +1.9% COP velocity	↑ subjective mental fatigue ↓ reaction time of cognitive task ↔ MFI (motivation), PSQI
Tassignon et al. (2020)	IG (12) CG (12)	4/8	Young (23 ± 2)	Stroop Task	90	Nature documentary	Proactive balance: Y-balance-test (average)	Low	↔ +0.7% (cm)	↑ mental fatigue, mental demand, temporal demand, frustration, effort ↓ cognitive performance ↔ motivation, EEG spectral power, Stroop-Task performance, accuracy (Eriksen-Flanker Task)
Varas-Diaz et al. (2020)	IG (15) CG (15)	15/0	Old (66 ± 6)	Stop-Signal Task	60	Nature documentary	Static balance: Stable parallel bipedal stance	High (sensory manipulation: eyes closed with sway referenced surface)	↓ +45.9% resultant CoM jerk	↑ fatigue ↓ wakefulness, parasympathetic activity (HRV), accuracy ↔ motivation, cognitive performance
Verschueren et al. (2020)	IG (14) CG (14)	4/10	Young (22 ± 1)	Stroop Task	90	Nature documentary	Proactive balance: Y-balance-test (average)	Low	↓ +1.0% (cm)	↑ mental fatigue, mental demand, temporal demand, effort, frustration, accuracy (Eriksen-Flanker Task) ↔ motivation, perception of task

(continued on next page)

Table 2 (*continued*)

Study	Participants			Fatigue protocol			Balance task		Outcomes	
	N	Sex (F/M)	Age (years)	Task	Duration (min)	Control	Balance component/test	Task complexity	Balance performance	Measures of fatigue/cognitive performance
										success, Stroop-Task performance ↓ cognitive performance

CG control group, *cm* centimeters, *CoM* center of mass, *CoP* center of pressure, *EEG* electroencephalography, *HRV* heart rate variability, *IG* intervention group, *MFI* Multidimensional Fatigue Inventory, *NASA-TLX* National Aeronautics and Space Administration – Task Load Index, *POMS* Profile of Mood Survey, *PSQI* Pittsburgh Sleep Quality Index.

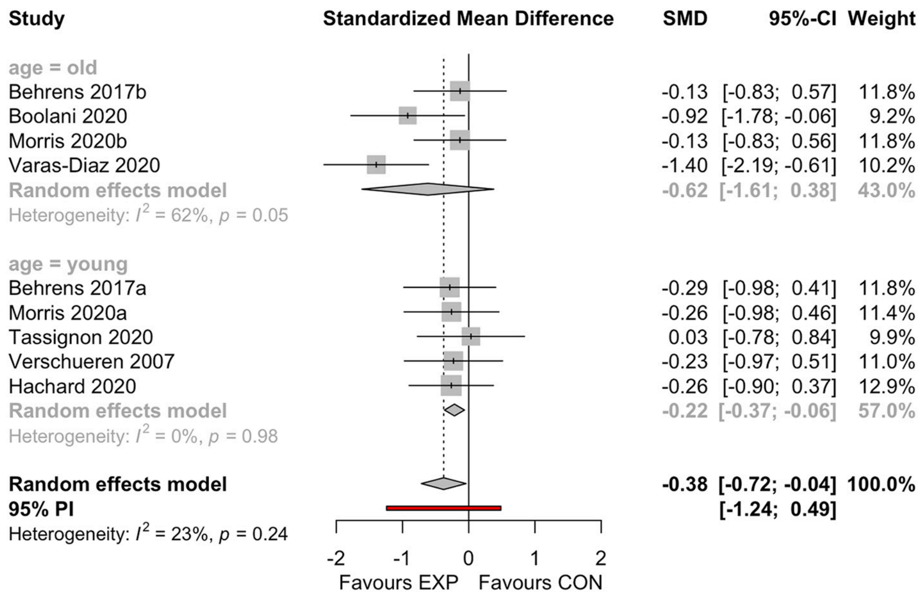

Fig. 3. Effects of mental fatigue versus passive control condition on balance performance in healthy young and older adults. *SMD* standardized mean difference, *CI* confidence interval, *PI* prediction interval.

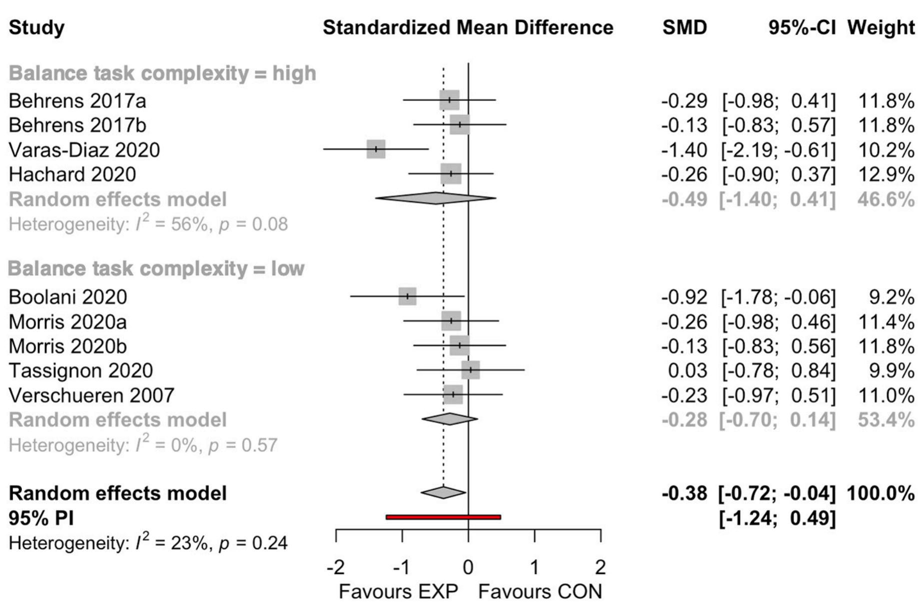

Fig. 4. Effects of mental fatigue versus a passive control condition on balance tasks with high and low complexity. *SMD* standardized mean difference, *CI* confidence interval, *PI* prediction interval.

selected the balance condition with the highest task complexity from each study. In our study sample, three studies assessed balance performance using complex tasks, i.e., by adding a cognitive task or manipulating sensory feedback (Behrens et al., 2017; Hachard et al., 2020; Varas-Diaz et al., 2020). However, we could not confirm that balance was affected to a greater degree in these studies. Notably, four studies assessed balance under increased postural demands, e.g., in single-leg stance or on an unstable surface (Hachard et al., 2020; Morris & Christie, 2020; Tassignon et al., 2020; Verschueren et al., 2020), which may have increased the heterogeneity of study results. Future research is encouraged to manipulate and quantify the attentional demand required to perform different balance tasks and investigate their potential interactions with mental fatigue.

Another point to consider is congruency between the fatigue task and the subsequent balance task. Exercise studies have shown that balance performance is highly-task specific and that even small differences between a balance exercise and a subsequent balance tests result in a diminished training response (Giboin et al., 2015). Conversely, it is possible that specificity also plays a role in mental fatigue, that is performance decrements are highest when the mental fatigue task or its underlying resources are closely related to the subsequent balance task. With respect to physical task characteristics, Van Cutsem et al. (2017) further argued that tasks requiring all-out efforts of short duration may be less affected by mental fatigue compared to tasks that involve sustaining an effort over a longer duration. None of the studies included in our meta-analysis displayed congruency between the fatigue and balance task. Although we cannot investigate this question, it is not unlikely that this lack of congruency may have contributed to the small overall effect size. Together, these findings demonstrate the complex interplay between fatigue and balance task characteristics and underline the need to systematically explore their relationship.

4.2. Characteristics of fatigue protocols

The fatigue tasks of the included studies varied in type, complexity, and duration. This raises the question whether fatigue was successfully induced and if the level and type of fatigue was comparable across studies. Unfortunately, the small study sample of our meta-analysis did not allow us to conduct a meta-regression analysis for task modalities or explore its dose-response relationships using subgroup analyses. We will therefore qualitatively discuss the fatigue interventions of the included studies.

One important aspect to consider is the type of task that was used to induce mental fatigue. The Stop-Signal Task, the Stroop color word test, and the Continuous Performance Task represent so-called central executive inhibition tasks, whereas the Psychomotor Vigilance Task and Rapid Visual Input Processing Task represent vigilance tasks that activate neural networks required for sustaining attention. Boolani et al. (2020) had participants perform a battery of different fatigue tasks, including serial subtractions and the Trail-Making Test, but also included executive inhibition tasks in their fatigue protocol. Neuroimaging studies show that inhibition tasks involve neural networks in the prefrontal cortex among others (Aron & Poldrack, 2005), while vigilance tasks activate neural networks in the frontal, parietal, occipital, thalamic, and cerebellar regions (Lawrence et al., 2003). However, there might be some overlap with respect to the neuromodulators used by these brain circuits, i.e., dopamine and noradrenaline, which suggests that both task types at least partially depend on the same resources (Brown et al., 2020; Noudoost & Moore, 2011). In support of these findings, Smith et al. (2019) directly compared the effects of time-matched vigilance and inhibition tasks on subjective ratings of fatigue and showed that both tasks resulted in similar levels of fatigue.

The duration of the fatigue protocols in the present meta-analysis ranged from 20 to 90 min (average duration = 67 min). This is a broad range and there is ongoing discussion as to whether the duration of the protocol mediates the fatigue response. Brown et al. (2020) report fatigue effects after interventions lasting only 3–5 min and argue that excluding studies based on protocol duration can introduce considerable bias in the analysis and affect its results. Using meta-regression analysis, they found no evidence of a linear dose-response relationship between protocol duration and physical performance outcomes. Likewise, Giboin and Wolff (2019) found no correlation between duration of the fatigue task and subsequent physical performance. In contrast, Habay et al. (2021) state that, according to their analysis, task duration may be relevant factor to consider, since interventions shorter than 15 min were repeatedly unable to induce notable levels of fatigue. The studies included in our meta-analysis had participants perform the mentally fatiguing tasks for 20 min or more, which is above the minimum duration currently under debate. However, it should be mentioned that Morris and Christie (2020), who employed the shortest fatigue protocol of all studies (20 min of Psychomotor Vigilance Task), reported increased levels of mental fatigue but did not observe any concomitant changes in balance outcomes.

Task duration should be discussed in relation to task complexity. In this regard, O'Keeffe et al. (2020) recently demonstrated that participants experienced mental fatigue after performing a cognitive single task continuously for 90 min but also reported decreased arousal levels, i.e. motivation. In contrast, performing more complex dual tasks for a shorter duration (16 min) resulted in mental fatigue without simultaneous changes in arousal. The authors conclude that shorter and more complex tasks may be better-suited for inducing mental fatigue because they prevent potential interference with under-arousal. In our study sample, fatigue was only induced with cognitive single tasks that potentially may have caused under-arousal. However, five of seven studies assessed motivation (i.e., an indicator of arousal), and found that ratings were similar before and after the fatigue intervention. This indicates that task complexity was not a confounding variable with regard to the magnitude of the fatigue response.

4.3. Potential mechanisms of fatigue

When trying to elucidate the fatigue-related decline in balance performance, it must be considered that balance depends on a complex multimodal system, influenced by cognitive resources (Whitman et al., 2001), sensory input (Lord & Dayhew, 2001), as well as muscular output and function (Daubney & Culham, 1999). Functional imaging studies have established the key role of supraspinal centers in postural control, such as the prefrontal cortex (PFC) (Jacobs & Horak, 2007; Ouchi et al., 1999; Taube et al., 2008; Yogev-Seligmann et al., 2008). Since the PFC is important for both postural control and executive function, it has been proposed as a potential source of cognitive-postural interference (Rochester et al., 2014). Imaging studies have also reported structural interference in other areas during cognitive-postural dual-tasking, such as the right insula (Papegaaij et al., 2017), emphasizing the decentralized nature of cognitive-postural interference. Although the mechanisms of how mental fatigue affects balance remain unknown, researchers have linked the effect to the reduction of cognitive resources required for postural control (Qu et al., 2020). In this regard, mental fatigue has been associated with decreased PFC activity (Shortz et al., 2015; Terentjeviene et al., 2018) and imaging studies show that individual differences in cognitive-postural balance performance are related to resource allocation in the lateral PFC (Stelzel et al., 2018). Additionally, frontal-basal ganglia circuitries are suspected to play role in the pathogenesis of mental fatigue in neurological disorders (Chaudhuri & Behan, 2004; Roelcke et al., 1997) and psychiatric disorders (Moeller et al., 2012) and thus also might underlie transient mental fatigue effects in healthy populations. While the present study is not able to answer the question which mechanisms govern the fatigue response, the manifestations of the observed fatigue response may provide insight.

Notably, physiological markers of mental fatigue were only assessed in three studies. Varas-Diaz et al. (2020) as well as Behrens et al. (2017) measured heart-rate variability and noted changes that were indicative of decreased parasympathetic activity. Pointing to studies that investigate the relationship between heart rate and mental stress, the authors state that mental fatigue may have decreased activity in brain areas that normally inhibit the sympathetic response and regulate the autonomous nervous system activity, including the PFC. Using electroencephalography, Tassignon et al. (2020) found that theta activity in the increased following a mentally fatiguing task, which they attribute to a decreased availability of attentional resources. These results indicate that physiological manifestations of mental fatigue may contribute to balance decrements. However, more focused investigations on this topic are required.

While subjective ratings of mental fatigue increased consistently across study groups, the results are equivocal regarding the behavioral manifestations of mental fatigue with respect to cognitive performance. While some studies report slower reaction times or reduced accuracy at the end of performing a continuous cognitive task (Hachard et al., 2020; Morris & Christie, 2020; Varas-Diaz et al., 2020), others did not find any effects at all or only in certain outcomes (Behrens et al., 2017; Tassignon et al., 2020; Verschueren et al., 2020). Although these results seem contradictory, they are in line with existing research. Indeed, Van Cutsem et al. (2017) noted that mental fatigue does not necessarily modify behavioral outcomes. They point towards studies that demonstrated compensatory effects of increased motivation at the end of a mental fatigue protocol despite previous indications of fatigue. Additionally, learning/practice effects may have compensated behavioral manifestations of fatigue in the cognitive domain (Noé et al., 2021). Researchers are encouraged to examine the different dimensions of the mental fatigue response, their relationship and potential interactions, e.g., whether trade-offs between these dimensions exist.

4.4. Effects of balance task complexity on balance performance

Knowingly, balance performance is susceptible to direct cognitive manipulations, such as increasing working memory load and or the degree of executive control by adding a secondary cognitive task (Behrens et al., 2017; Stelzel et al., 2017). Evidence also suggests that cognitive involvement in balance performance is greater during complex balance tasks. For example, Karim et al. (2013) reported greater activation in the temporal-parietal cortical areas when proprioception and vision was diminished and Teo et al. (2018) showed that sensory manipulation resulted in increased dorsolateral PFC activation during quiet stance in older adults. A recent study by St George et al. (2021) investigated the combined effects of sensory manipulations and cognitive-postural dual-tasking in healthy young and older adults and found that PFC activity increased during more complex balance tasks. The authors conclude that this increase signifies compensation for sensorimotor deficits in an effort to maintain stability (St George et al., 2021).

In accordance with the theory of limited cognitive resources (Kahneman, 1973; Wickens, 1980), balance tasks that require greater cortical involvement may cause interference because postural and cognitive processes rely on overlapping cortical areas. When mentally fatigued, participants experience a reduction of cognitive resources, which further limits their ability to coordinate postural and/or cognitive tasks. Against this background, we expected mental fatigue to interfere with postural control in a task-dependent manner. We found that the effects of mental fatigue on balance were larger in more complex balance tasks ($SMD_{wm} = -0.49$) compared to less complex balance tasks ($SMD_{wm} = -0.28$), but the results of our subgroup analysis (balance tasks with high complexity vs. balance tasks with low complexity) did not reach significance. Several reasons may have contributed to this outcome. First, the population investigated in the present meta-analysis consisted of healthy young and older adults without any cognitive impairments, so it is possible that these individuals were able to prevent behavioral manifestations of mental fatigue by allocating larger attentional demands to maintaining balance. There is also evidence that individuals prioritize balance over cognitive performance in potentially fall-threatening situations (Adkin et al., 2002), suggesting that healthy adults may have adapted a "posture-first" strategy in more complex balance tasks. In support of these findings, studies that included cognitive-postural dual tasks found cognitive performance to decrease following the mental fatigue task (Behrens et al., 2017). Additionally, some studies report using task instructions, such as telling participants to minimize sway (Hachard et al., 2020). Possibly, this led to individuals shifting their attentional focus to the postural task, which may have helped to maintain balance. These findings, in combination with the observed yet insignificant differences between balance tasks with varying degrees of complexity, suggest that the high cognitive status of healthy adults may have played a role in ameliorating the detrimental effects of mental fatigue on balance.

4.5. Effects of age

Age-related structural changes in the musculoskeletal (e.g., loss of muscle mass and function) and central nervous systems (e.g., reductions in grey matter volume, white matter hyperintensities) knowingly result in a decline of postural control, prompting the need for functional compensation to ameliorate balance declines (Bahureksa et al., 2017; Goodpaster et al., 2006; Laughton et al., 2003; Nagai et al., 2011). Older adults' postural control is characterized by less automatic postural control and greater supraspinal contribution (Baudry, 2016; Papegaaij et al., 2014), which may cause interference when concurrently performing cognitive tasks (Herath et al., 2001). Older adults have also been shown to allocate additional attentional resources towards maintaining balance, as shown by increased activation in the PFC (Shumway-Cook et al., 1997). Interestingly however, older adults demonstrate ceiling effects in PFC activity and became less stable stance when performing complex balance tasks, i.e., when sensory feedback is reduced and a concurrent cognitive task is performed (St George et al., 2021). This suggests that PFC activity can only compensate for sensorimotor deficits in balance tasks with low task complexity, because in these situations the limits of cognitive resources required for balance control are not yet exceeded. Mental fatigue reduces cognitive resources (Van der Linden et al., 2003) and may further limit older adults' ability to restore or maintain balance via compensatory resource allocation. Although aging has been shown to exacerbate the effects of mental fatigue on balance performance (Behrens et al., 2017), our results cannot confirm this. Despite differences in effect size (old: $SMD_{wm} = -0.62$; young: $SMD_{wm} = -0.22$), subgroup analysis revealed no significant age-effects on balance in the responses to fatigue. Still, differences in subject characteristics, research design, and employed balance tasks may have masked an age-effect. It is also possible that older adults did not fully exert themselves. In this regard, Morris and Christie (2020) report that younger adults experienced significantly higher levels of fatigue compared to older adults. Since studies have demonstrated that older people are more willing to engage resources in support of demanding cognitive activities (Ennis et al., 2013), it is also possible that older compared to young adults were more motivated to perform well in the balance tasks. Notably, our subgroup analysis comprised only five study groups of young healthy adults and four study groups of older adults, which limits the statistical power to detect age-differences. All in all, current evidence cannot confirm that healthy older adults' balance is particularly vulnerable to mental fatigue. Future studies that employ both balance and cognitive tasks with varying levels of difficulty and adaptive fatigue protocols are needed to examine in how far the effect of mental fatigue on balance performance is mediated by age.

4.6. Limitations and future directions

Several aspects should be considered when interpreting the results of this meta-analysis. First, our study sample only consisted of 9 study groups from 7 different studies. Although meta-analyses with a similar number of studies have been published and we adhered to the recommendations of Jackson and Turner (2017), which state that at least five studies should be included in random-effects meta-analyses to generate meaningful results, the size of our study sample imposed some limitations with regard to our analyses. For example, we were not able to perform a meta-regression to examine if any modalities of the mental fatigue protocol, i.e., type of task or duration, predict changes in balance performance because the number of studies was below the minimum recommended in the Cochrane Handbook (Higgins et al., 2019). Likewise, we were not able to perform subgroup analyses on the duration or type of cognitive task used in the fatigue protocol and determine its effect on the response to fatigue. First steps have been made in this direction (Smith et al., 2019) but future studies should systematically manipulate protocol variables and establish their dose–response relationships for different populations, such as young and older adults.

Notably, individual balance components represent relatively independent motor skills (Magill & Anderson, 2010). Thus, mental fatigue may affect balance components differently, possibly due to different underlying structures and mechanisms being involved. Unfortunately, the small number of eligible studies prevented us from performing subgroup analyses, which is why we cannot postulate whether static balance, dynamic balance, reactive and proactive balance are affected differently by mental fatigue. We acknowledge that pooling outcomes from different balance components in one meta-analysis is not a preferred solution. We therefore recommend that future studies should systematically assess the effects of mental fatigue on different balance components.

Although our analyses revealed that mental fatigue reduces balance performance, our meta-analysis does not provide information about how these decrements translate into functional outcomes, such increased risk of fall rates or injuries. It should also be considered that our analysis only focused on healthy adults. Hence, it is not known if the responses to fatigue would be similar in adults with mild cognitive impairments or subclinical medical conditions.

Finally, the validity of experimentally induced fatigue on balance outcomes has never been determined by comparing these results with those obtained in individuals who report fatigue. It is possible the mechanisms involved differ between these two conditions, potentially limiting the inferences drawn from experimental data to naturally occurring fatigue conditions.

5. Conclusions and practical implications

This systematic review and meta-analysis shows that mental fatigue has small but significant effects on overall balance performance. Effect sizes were smaller for young compared to older adults, but the results did not reach the level of statistical significance. Similarly, the observed effect for balance tasks with high compared to low task complexity was larger in magnitude, but the difference was not significant either. Since mental fatigue is commonly reported among healthy adults, the results of our meta-analysis serve to raise awareness for the effects of cognitive resource depletion on physical performance in the general adult population. Although healthy adults do not appear to be particularly vulnerable to balance threats, mental fatigue might play an important, yet not sufficiently studied role in research. Future studies should develop methods that measure mental fatigue status with high sensitivity and attempt to identify fatigue-thresholds that put individuals at a greater risk of balance loss. Furthermore, the present results encourage the design and implementation of cognitive-postural training interventions which aim at increasing individuals' fatigue-resistance in different contexts. In addition, research into the effects of mental fatigue on different components of balance performance should be intensified in an effort to elucidate the role of cognitive resources in motor control.

CRediT authorship contribution statement

All authors listed have made substantial, direct and intellectual contribution to the work, and approved it for publication.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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