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RESEARCH ARTICLE

Perceived cognitive fatigue has only marginal effects on static balance control in healthy young adults

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Abstract

We examined the influence of perceived cognitive fatigue on static balance control in healthy young adults to gain greater clarity about this issue than provided in previous research. Based on the prevailing assumption in pertinent literature, we hypothesized that the influence of cognitive fatigue on balance control depends on the attentional effort required by the balance tasks being performed. To test this hypothesis, 44 young adults (24 women and 20 men) were alternately assigned to either the experimental group that was cognitively fatigued (using the 16-min TloadDback-task with individualized settings) or the control group (who watched a documentary). Before and after the intervention, the participants performed six balance tasks that differed in (attentional) control requirements, while recording the center of pressure (COP). From these time series, sway variability, mean speed, and sample entropy were calculated and analyzed statistically. Additionally, perceived cognitive fatigue was assessed using VAS scales. Statistical analyses confirmed that the balance tasks differed in control characteristics and that cognitive fatigue was elevated in the experimental group, but not in the control group. Nevertheless, no significant main effects of cognitive fatigue were found on any of the COP measures of interest, except for some non-robust interaction effects related primarily to sample entropy. These results suggest that, in young adults, postural control in static balance tasks is largely automatic and unaffected by task-induced state fatigue.

Keywords Mental fatigue · Postural regulation · Cognitive resources · TloadDback · Sample entropy

Introduction

Performing a cognitive task for a prolonged period of time or at a high intensity will inevitably lead to a state of fatigue (Boksem et al. 2005; Hockey 2013), also known as mental fatigue, mental workload, cognitive fatigue, and similar terms. The characteristics of this cognitive task-induced state fatigue (CF) are twofold. On the one hand, it can manifest itself in an increased subjective perception of fatigue, called perceived cognitive fatigue (Enoka and Duchateau 2016; Behrens et al. 2023). This component of fatigue is typically experienced as feeling tired, worn out or lethargic (Hockey 2013), a sensation of requiring some rest, or a mismatch between effort expended and actual performance (Skau et al. 2021). Perceived cognitive fatigue is dependent on the psychological state of the individual and therefore influences effort perception, affective valence, self-regulation, and time perception (Behrens et al. 2023). On the other hand, task-induced fatigue can lead to a decrease in cognitive performance and is therefore termed cognitive performance fatigue (Behrens et al. 2023). This component of fatigue refers to the depletion of executive and attentional functions, for example as evidenced by longer times needed to process, plan, and respond to stimuli (Tanaka 2015; Borragan et al. 2017). Other typical manifestations are a degraded response accuracy and an increasing difficulty to focus on relevant information while suppressing irrelevant stimuli (Borragan et al. 2017). The exact psychophysiological mechanisms linked with cognitive performance fatigue are still under discussion, but encompass factors such as modified brain

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activation, diminished motivation, and the decline of cognitive resources like attention (Behrens et al. 2023).

Prolonged or intense cognitive performance can lead to a decrease in motor accuracy, even when the motor system is not directly involved in the activity. A potential mechanism behind this interaction is that the cognitive task over time depletes some of the resources that are also needed to maintain accurate motor performance (Brahms et al. 2022). Two recent systematic reviews examined the interaction between task-induced cognitive fatigue and the performance of a motor task, namely maintaining postural control in healthy individuals (Brahms et al. 2022; Pitts and Bhatt 2023).[1] Three important observations can be gleaned from those reviews. First, the literature is limited and consists of approximately 10 experimental studies (depending on the adopted inclusion and exclusion criteria). The small body of literature highlights the need to broaden the database to be able to draw reliable conclusions. Second, both reviews, as well as the papers cited therein, reveal a potential role of CF on especially the cortical regulation of balance, although effects of subcortical and spinal control loops cannot be ruled out. Therefore, effects of CF are expected to occur when the balance task requires greater cognitive involvement, as in challenging postural situations, and/or when the automatic regulation of balance is hampered due to pathology. The question is whether these expectations hold true. However, as it stands, and this is the third observation, the evidence for a robust influence of CF on posture is inconclusive. Whereas Brahms et al. (2022) concluded unequivocally that CF can adversely affect balance in healthy young adults, Pitts and Bhatt (2023) came to a more nuanced conclusion as some studies only showed modest, partial, or even null effects. Differences in research findings might have been due to various methodological factors, including the method to induce CF, the type of balance control (e.g., volitional versus reactive), the experimental tasks, the balance measures, the study population, and the statistical power.

The present study was conducted to help resolve the existing ambiguity in study results by assessing the effect of CF on static balance control, focusing on a specific instance of postural stability, namely quiet upright standing. Thus far only three studies have examined this particular instance of postural stability in the context of CF (Deschamps et al. 2013; Hachard et al. 2020; Varas-Diaz et al. 2020) and all three found an effect of CF on postural sway. Static postural control is a fundamental motor skill for performing a broad variety of daily life activities in a safe and efficient manner (Hachard et al. 2020). It has long been assumed that upright standing is an automatic and largely reflex-driven process, which thus requires little attentional regulation (Nashner 1976; Kerr et al. 1985; Teasdale et al. 1993; Takakusaki et al. 2004). However, under certain experimental conditions, such as cognitive–postural dual-tasks and sensory manipulations, it can be observed that attentional resources are tapped, even in simple postural tasks like quiet stance (Papegaaij et al. 2014; Ruffieux et al. 2015; Teo et al. 2018). In such instances, an increase in cortical activation has been observed compared to performing the same task without visual or proprioceptive manipulations or having to perform a concurrent cognitive task (Prado et al. 2007; Bergamin et al. 2014; Teo et al. 2018). This increase in cortical activity might reflect elevated attentional demands to ensure postural stability or task complexity (Lajoie et al. 1993; Papegaaij et al. 2014). Another observation pointing towards a possible link between postural stability and cognitive resources is that older individuals or individuals with mild cognitive impairment are less stable during quiet stance and exhibit a slower gait speed compared to their cognitively fitter counterparts (Muir et al. 2012; Deschamps et al. 2014; Grobe et al. 2017; Behrens et al. 2018). Both observations raise the question whether CF adversely influences the performance of static balance tasks.

A crucial factor in achieving this aim resides in the selection of a suitable method to induce CF. The two systematic reviews reveal various methods that have been employed for this purpose, and which differ considerably in terms of duration (Brahms et al. 2022; Pitts and Bhatt 2023). Most CF studies published to date used a prolonged computerized task to induce CF, based on the notion that CF needs extended time to accumulate. Examples are the 90-min AX-CPT (Hachard et al. 2020; Noé et al. 2021), the 90-min Stroop Task (Tassignon et al. 2020; Verschueren et al. 2020), the 30-min psychomotor vigilance task (Deschamps et al. 2013), and the stop-signal task performed for either 90 (Behrens et al. 2018) or 60 min (Varas-Diaz et al. 2020). Note that these tasks focus on various interlinked cognitive processes, such as sustained attention, inhibitory control, and response inhibition (O'Keeffe et al. 2019; Smith et al. 2019; Behrens et al. 2023).

Although all these tasks reliably induced CF on a group level, they did not take individual differences in susceptibility to CF into account (Noé et al. 2021). However, previous research has revealed large individual differences in susceptibility to CF (O'Keeffe et al. 2019). Therefore, we chose the TloadDback task for inducing CF (Borragan et al. 2017), because this task has the advantage that its settings can be adapted to an individually predefined maximum cognitive load, thus rendering the degree of CF equivalent across participants. Another advantage of the TloadDback task is its relative short

[1] While these reviews, as well as most of the papers cited, often use the term 'mental fatigue', we have decided to adopt more contemporary terminology, following the framework proposed by Behrens et al. (2023). We will use the term 'cognitive fatigue' when addressing both the perceived and performance fatigue.

duration of 16 min. This is achieved by individualization, but also the type of task (working memory dual task; Behrens et al. 2023).

We examined the effects of cognitive fatigue on postural stability in healthy young adults, because if such effects exist in this population, they would most likely also exist in other physically and mentally less prone populations. Our main hypothesis was that CF has an adverse effect on balance control during quiet upright standing, as evidenced by changes in the characteristics of the center-of-pressure (COP) recordings. Specifically, we expected the sway variability and the speed of the COP to increase, and the degree of randomness (sample entropy) in the COP time series to decrease with CF. All these measures have been used in comparable studies (Deschamps et al. 2013; Hachard et al. 2020; Noé et al. 2021), thus allowing comparison of findings across studies.

Furthermore, we hypothesized that the influence of CF on balance control depends on the attentional effort required by the balance tasks being performed. To this end, we included several static balance tasks in the experimental design that differed in complexity and attentional demands. To achieve this, we combined two postures (hip-broad and tandem stance) with three task manipulations (eyes open, eyes closed, and dual task). Balance control was hypothesized to be less stable and more challenging, requiring greater attentional control, in tandem stance compared to hip-broad stance, as well as with eyes closed compared to eyes open, while the addition of a cognitive task was expected to reduce the inward focus of attention on balance (Roerdink et al. 2006; Donker et al. 2007; Stins et al. 2009; Potvin-Desrochers et al. 2017; Becker and Hung 2020; Richer and Lajoie 2020). The addition of a cognitive dual task was expected to reduce attentional control over the balance task being performed.

To test our research hypotheses, we first verified that the postural manipulations indeed resulted in different COP patterns in the absence of CF. After all, should these differences not be present at baseline, then the hypothesis that the influence of CF increases with task complexity cannot be investigated. Based on previous studies, we expected that tandem stance is less stable than hip-broad stance, that standing with eyes closed is less stable than with eyes open, as reflected in increased postural sway and reduced COP regularity in both comparisons, and that adding a cognitive dual task leads to reduced postural sway and increased COP complexity, presumably due to a reduction in attentional focus (Donker et al. 2007; Potvin-Desrochers et al. 2017; Rhea et al. 2019; Becker and Hung 2020; Yamada and Raisbeck 2021). These expectations were verified by examining the COP fluctuations prior to the CF intervention. The protocol of this study, together with the hypotheses and statistical analyses, was pre-registered on Open Source Framework (OSF): https://osf.io/2e9gs.

Methods

Participants

The sample size required for this study was calculated using G*Power (Faul et al. 2007). For a repeated-measures analysis of variance (ANOVA) with within-between interaction (effect size $f = 0.25$, α error probability = 0.01, power = 0.95, 2 groups, and 6 measurements), 36 participants would be required. To remain on the conservative side and anticipate the possibility of participant or data loss, a convenience sample of 44 young adults were recruited. The sample mostly comprised students and employees of the Vrije Universiteit Amsterdam. Participants had to be between 20 and 35 years old and healthy, without regard of sex. All participants (24 female and 20 male, average age 25.86 ± 3.26 years; mean ± standard deviation) were asked not to engage in vigorous exercise 48 h before the experiment and to consume no beverages containing alcohol, caffeine, or other stimulants (Hachard et al. 2020) for minimally 2 h before the experiment. Participants were further requested to avoid sleep deprivation the night before the experiment as sleep quantity and quality can interfere with both cognitive and motor performance. The same requirements had to be fulfilled before the familiarization session, in which the stimulus duration time was determined (see below). Participants were asked about their sleep before the experiment by posing the following two questions: (1) How many hours of actual sleep did you get at night?, and (2) How would you rate your sleep quality? (1 = very good, 2 = fairly good, 3 = fairly bad, 4 = bad). The two questions were taken from the Pittsburg Sleep Quality Index (Buysse et al. 1989) and selected because they captured the relevant information about sleep the night before.

Protocol

To assess the effect of CF on postural stability, a mixed design was used. Participants were alternately (based on the order of enrollment) assigned to either the experimental or control group. The experimental group was cognitively fatigued using the 16-min TloadDback task, whereas the control group watched a neutral documentary of equal duration. The assessment of postural balance before and after the intervention consisted of six balance tasks (two postures under three conditions); all of which were performed on a force plate. To avoid an order effect and consequent potential confounding of the results, the six balance tasks were performed in randomized order. Right before the pre-intervention balance measurements, all participants were allowed a few minutes to familiarize themselves with the experimental tasks and setup until they felt comfortable. Right before the post-intervention balance tests, subjective levels of cognitive fatigue were evaluated using visual analog scales (VAS). If a participant was unable to maintain a certain balance task, the trial in question was repeated immediately. Participants were allowed a maximum of three attempts to successfully complete any given balance task. If all three attempts were unsuccessful, or if recordings turned out to be invalid, the trials were excluded for that balance task of the respective participant, while successful recordings of the other tasks were still included in the analysis.

The experimental protocol is shown schematically in the Supplementary Fig. S1.

Interventions

Cognitive state fatigue was induced by the Time load Dual-back (TloadDback) task (Borragan et al. 2016, 2017). It combines two information processing tasks, the *N*-back working-memory updating task and the odd/even decision task. During the TloadDback, letters and digits appear alternately (letter/digit/letter/…) on a computer screen. The participant was instructed to press "2" for even numbers and "3" for odd numbers on a numeric keyboard using their right hand. Furthermore, they were instructed to indicate whether the depicted letter equals the letter that was presented *N* letters back (with $N = 1$) by pressing the space bar with their left hand. To induce similar levels of CF in all participants the task was adapted such that it imposed the same cognitive load on all participants. This was done by adapting the duration for which each stimulus was displayed on the screen, termed the stimulus time duration (STD). If the task is being sped up by gradually reducing the STD, more and more effort is required to maintain accurate performance, thus arguably depleting cognitive resources and increasing CF (Barrouillet et al. 2007). Following the recommendations of Borragan et al. (2017), the STD was reduced until an accuracy of > 85% could no longer be sustained. The minimal possible STD of each participant in the experimental group was determined in an extra session held 1–7 days prior to the actual experiment. To minimize the effect of day-to-day differences, the actual experimental session was scheduled at the same time (± 1 h) of day as the first session.

For the control intervention a 16-min excerpt of the BBC documentary "Earth" (Fothergill 2007) was chosen as this control task was also used in previous studies, thus allowing comparison of results (Hachard et al. 2020; Varas-Diaz et al. 2020).

Assessment of perceived cognitive fatigue

Perceived cognitive fatigue was assessed with a digital visual analog scale (VAS) using the AVAS-Software (Marsh-Richard et al. 2009). To avoid response shift bias (Howard 1980), a retrospective pretest design was used in which the participants only performed the VAS after the intervention (Gorrall et al. 2016). Participants were asked to rate their subjective levels of perceived fatigue on the VAS in both an absolute and a relative manner directly after the intervention. The scale to determine the absolute levels of perceived CF post-intervention ranged from 'not at all fatigued' ($\triangleq 0$) to 'extremely fatigued' ($\triangleq 100$). Subsequently, they were asked to reflect and compare their degree of CF after to before the intervention, on a scale ranging from 'much less fatigued' ($\triangleq -50$) to 'much more fatigued' ($\triangleq 50$), with 0 indicating no change.

Assessment of postural control

Postural control was assessed in two static balance postures: (1) hip-broad stance, with feet positioned hip-broad and parallel to each other, toes pointing forward, and (2) tandem stance, with one foot placed directly in front of the other with the heel of the front foot touching the big toe of the back foot. No instructions were given regarding which foot to place in front. Both postures were carried out in three conditions: (i) eyes open, (ii) eyes closed, and (iii) dual task (balance task combined with a cognitive task). The cognitive task consisted of silently counting backward in steps of seven from a randomly given number between 150 and 300 (Stins et al. 2011). Participants were instructed to prioritize the balance task over the cognitive task. The performance of the cognitive task was not analyzed.

Postural sway was recorded with a (1 × 1 m) custom-made strain gauge force plate (100 Hz sampling rate), consisting of eight force sensors, four of which measured the forces on the *z*-axis (vertical), two the forces on the *x*-axis, and two the forces on the *y*-axis. The resulting eight signals were automatically converted by the force plate's underlying program to a COP time series in the medio-lateral (ML) and anterior–posterior (AP) direction. The recording time was set to 60 s, since recording times of 60 s and longer are known to be beneficial to detect differences between groups when calculating sample entropy (Montesinos et al. 2018). Participants were instructed to sway as little as possible while performing the balance tasks and to focus on a circle attached at eye height 2 m in front of them for the tasks they performed with open eyes (Stins et al. 2009).

The recorded data were analyzed in MATLAB (Mathworks, Inc., Version R2022a). First, the COP time series were processed and low-pass filtered at 12.5 Hz using a bi-directionally second-order Butterworth. Subsequently, the COP time series were analyzed in the ML and AP directions separately by investigating commonly used linear COP measures, i.e., sway variability (standard deviation) and mean speed, as well as nonlinear COP measures, i.e., sample entropy (degree of randomness; Jeka and Lackner 1994; Raymakers et al. 2005; Duarte and Freitas 2010; Warnica et al. 2014; Dos Santos et al. 2019).

Sway variability

The standard deviation was calculated as a measure of sway variability:

$$\frac{1}{N}\sum_{i=1}^{N}\left(x_i-\overline{x}\right)^2,$$

where N is the number of samples, x_i the displacement at time t_i, and $\overline{x}$ the time series mean.

Mean speed

The mean displacement speed was calculated as the mean of the absolute values of the difference quotients of the displacements for the time series in question:

$$\frac{1}{N-1}\sum_{i=1}^{N-1}\frac{\left|x_{i+1}-x_i\right|}{\Delta t},$$

where N is the number of samples, x_i the displacement at time t_i, and Δt the time window between two samples. Since the mean speed is independent of the sampling time, it allows for a clean comparison across studies.

Sample entropy

Richman and Moorman (2000) defined the sample entropy in terms of conditional probabilities of similar sequences. Sample entropy $SampEn(m, r, N)$ is the negative value of the natural logarithm of similarity counts of $m+1$ points (A) over similarity counts of m points (B) among all points (N) of the sequence, where similarities are reached when distances between sample vectors are below a cutoff radius r:

$$SampEn(m,r,N) = -\ln\left[\frac{A^{m+1}(r)}{B^m(r)}\right] = -\ln\left[\frac{\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}\left[\text{number of times that } d\left[\left|x_{m+1}(j)-x_{m+1}(i)\right|\right]<r\right.}{\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}\left[\text{number of times that } d\left[\left|x_m(j)-x_m(i)\right|\right]<r\right.}\right].$$

It is well known that the calculation of sample entropy is rather sensitive to the number of points/template length m, similarity tolerance r, and the total data number of data points N. We therefore calculated the sample entropy using two different parameter settings, based on two methods, which have both been recommended in the literature:

1. Lake et al. (2002) provided a method to define parameters based on minimizing the maximum relative error of sample entropy, which resulted in $m=3$, $r=0.05$, and $N=6000$. This method is well established and commonly used in the analysis of physiological signals.
2. Montesinos et al. (2018) developed recommendation for parameter settings specifically for the analysis of COP time series, which are $m=4$, $r=0.25$, and $N=6000$.

Sample entropy values were calculated in MATLAB using a script by Martínez-Cagigal (2018).

Statistical analysis

First, all COP data (i.e., pre- and post-intervention) were analyzed for completeness and abnormalities, such as outliers. To reduce the impact of these outliers on the statistical analysis the 'winsorizing' method was applied to each measure. This data-clipping method replaces the score of an outlier with a determined minimum/maximum (Field 2018). Specifically, if, $x <$ mean $- 2 \cdot$ SD or $x >$ mean $+ 2 \cdot$ SD, x was replaced by the minimum or maximum value (mean $- 2 \cdot$ SD, mean $+ 2 \cdot$ SD, respectively). The winsorized COP outcome measures were used in the subsequent analyses.

Two sets of repeated-measures ANOVAs with a mixed 2 (group) × 2 (posture) × 3 (condition) design were performed, followed by post hoc tests for significant results in the form of pairwise comparisons with Bonferroni correction.

The first set of ANOVAs examined whether the postural control during the six balance tasks indeed differed in the expected manner by comparing the COP outcome measures across those tasks. The factor group was added in this analysis to evaluate possible differences between the experimental and control group before the intervention (i.e., at baseline). The second set of ANOVAs assessed the influence of CF on postural stability by comparing the effect of the interventions on the COP outcome measures for different postures and conditions, i.e., across the six balance tasks. For this purpose, relative symmetric change scores for all three COP measures were calculated as follows:

$$\Delta\ \mathrm{COP} = \frac{\mathrm{COP}_{post} - \mathrm{COP}_{pre}}{\frac{1}{2}\left(\mathrm{COP}_{post} + \mathrm{COP}_{pre}\right)}.$$

Dividing the absolute change score by the arithmetic mean is a standard procedure for data normalization to account for fluctuations in a pair of variables, provided that both are larger than zero (Vartia 1976; Burr and Nesselroade 1990).

The resulting ΔCOP measures were analyzed by conducting a repeated-measures ANOVA with the described design for each COP measure separately. In addition to the main effects, interaction effects were examined by means of post hoc-tests with a Bonferroni correction. Effect sizes are reported as partial eta squared (η_p^2) for all main and interaction effects. By convention, 0.01 represents a small effect, 0.06 a medium effect, and 0.14 a large effect (Cohen 1988).

Before conducting the ANOVAs, we assessed whether the data met the assumption of normality and sphericity (ε) by carrying out Kolmogorov–Smirnov (K–S) tests with Lilliefors correction and Mauchly's test of sphericity. If the sphericity assumption was violated, the Greenhouse–Geisser correction was applied (Field 2018). Sleep quality and quantity, as well as the subjectively rated levels of induced cognitive fatigue, were assessed by Mann–Whitney tests. For all tests, the level of significance was set at $p < 0.05$. All statistical analyses were performed in SPSS Statistics for Windows, version 27 (SPSS Inc., Chicago, IL., USA). Means and standard errors are reported in the statistical results unless specified otherwise.

Results

Participants

All participants except one male participant from the experimental group were included in the analysis. The participant in question was excluded because he was unable to safely perform the balance tasks. After the participant's exclusion, the experimental group consisted of 11 female and 10 male participants with a mean age of 25.6 ± 3.8 years, while the control group consisted of 13 female and 9 male participants with a mean age of 26.1 ± 2.7 years.

Initial analysis of the COP outcome measures

An initial analysis of all pre- and post-COP outcome measures revealed that a few of them contained extreme values (46 out of 1032 investigated variables), which were adjusted by means of winsorizing. The Kolmogorov–Smirnov (K–S) tests with Lilliefors correction showed that the COP data were distributed normally. The Mauchly's test of sphericity indicated a departure from sphericity for some variables, following which the Greenhouse–Geisser correction was applied.

COP measures before intervention

As expected, the manipulation of the balance tasks had marked effects on the COP measures of the participants (see Fig. 1).

The effectiveness of the balance task manipulation was also evident from the results of the repeated-measures ANOVAs that were performed on the pre-intervention COP outcome measures. These results are collected in the Supplementary Tables 1 and 2.

Three noteworthy findings can be gleaned from these tables. First, as expected, significant main effects of posture occurred. The tandem stance proved more difficult to maintain than the hip-broad stance, as evidenced by significantly larger sway variability and higher speeds in both the ML and AP direction. Posture also had a significant effect on the sample entropy in both directions when using Montesinos et al.'s method, but only in the ML direction when using Lake et al.'s method. The sample entropy values were significantly lower for the tandem than the hip-broad stance, indicating tighter postural control.

Second, significant main effects of condition were found for all three COP outcome measures. Post hoc analyses revealed that sway variability and mean speed values were significantly higher when standing with closed eyes compared to standing with eyes open or adding a cognitive dual task. As expected, postural control is more difficult and hence less stable with eyes closed. Furthermore, for both calculation methods the sample entropy measures were significantly higher in the dual task compared to either the eyes open or eyes closed condition.

Third, significant posture x condition interactions were found for sway variability and mean speed in both directions, but not for sample entropy. Post hoc tests revealed that the effect of posture was amplified with eyes closed, resulting in even larger sway variability and higher mean speeds.

Besides showing that the balance task manipulations were effective in creating marked differences in COP behavior, the ANOVA on the pre-intervention COP outcome measures revealed no significant differences between the experimental and control group. Hence, no relevant systematic differences

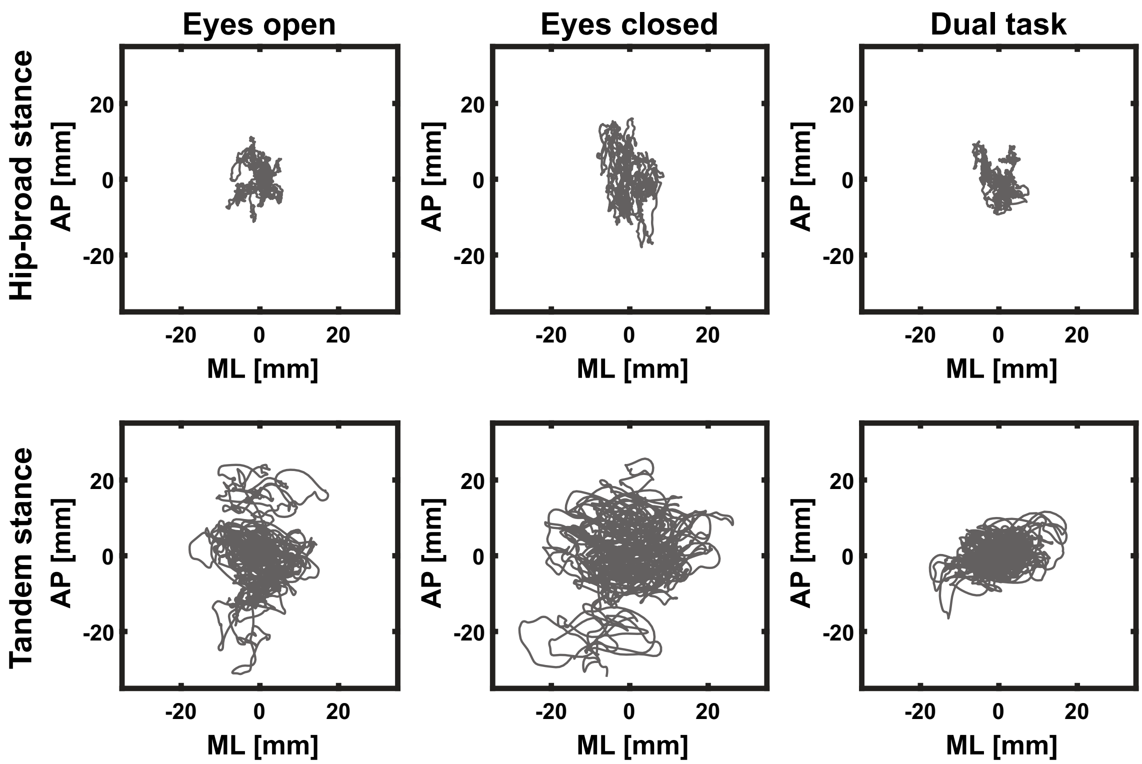
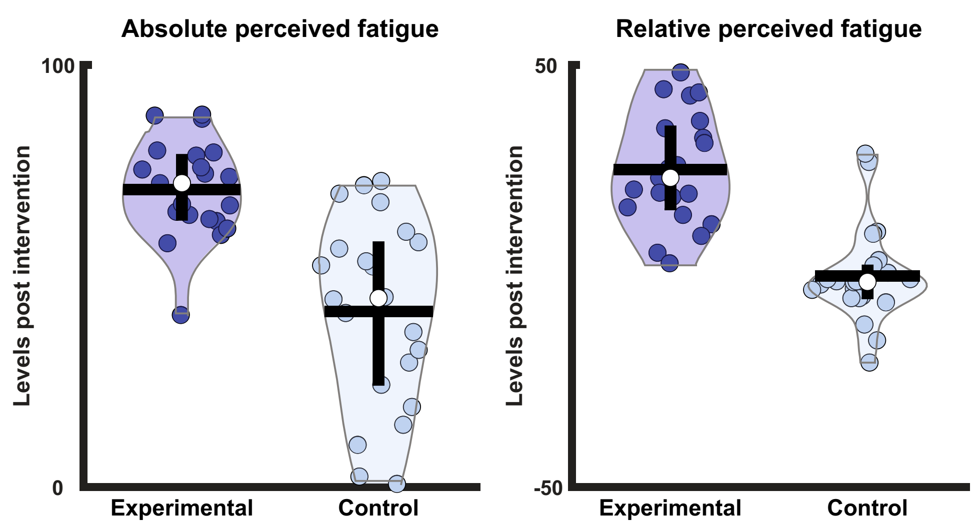


Fig. 1 COP trajectories of a representative participant for the six balance tasks before intervention

Fig. 2 Violin plots of subjective levels of induced CF; Left panel: absolute subjective level of CF after the interventions (TloadDback [dark blue] vs. documentary [light blue]); right panel: relative subjective level of CF after compared to before the intervention. Each dot represents one participant, and the size of the violin the spread of the data. Horizontal bar represents the mean, vertical bar represents the interquartile range, and the white center dot represents the median



in postural control were present between both groups before intervention.

Sleep quantity and quality

The mean rated sleep quantity of the participants in the experimental group was 7.5 ± 0.9 before both the familiarization and intervention session, while that in the control group was 7.3 ± 1.0 before their intervention session. The mean rating of the sleep quality of the participants in the experimental group was 1.8 ± 0.8 before the familiarization session and 2.0 ± 0.6 before the intervention session, while that in the control group was 1.9 ± 0.5 before their intervention session. Mann–Whitney tests revealed no significant differences between both groups regarding sleep quantity, $U = 191.00$, $p = 0.32$, $r = -0.15$, and quality, $U = 261.00$, $p = 0.39$, $r = -0.13$, before the interventions nor between the familiarization

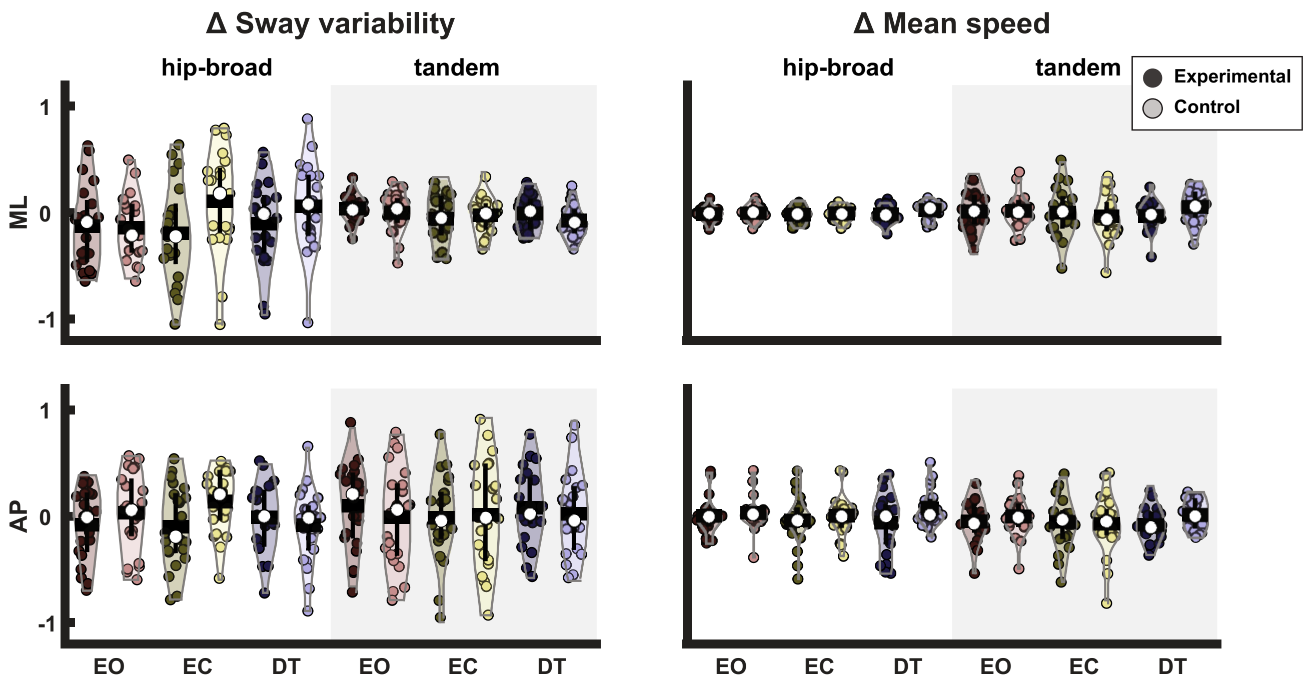


Fig. 3 Left panels: relative change of sway variability; right panels: relative change of mean speed in ML (above) and AP (below) direction. Experimental group [dark colors], control group [light colors]. Each dot represents one participant, and the violin the spread of the data. Horizontal bar represents the mean; vertical bar represents the interquartile range, and the white center dot represents the median

and intervention sessions of the experimental group: sleep quantity, $U = 208.50$, $p = 0.76$, $r = -0.05$ and sleep quality, $U = 254.50$, $p = 0.32$, $r = 0.16$.

Levels of task-induced perceived cognitive fatigue

The levels of perceived CF induced by the interventions are visible in Fig. 2. Following the interventions significantly higher absolute levels of CF were reported by the experimental group ($M = 70.54$, SE $= 2.51$) than the control group ($M = 41.59$, SE $= 4.77$), $U = 53.00$, $p < 0.001$, $r = -0.66$. The relative perceived CF was rated significantly higher by the experimental group ($M = 25.20$, SE $= 2.88$) than the control group ($M = 0.05$, SE $= 2.43$), $U = 33.00$, $p < 0.001$, $r = -0.73$. These results indicate that the TloadDback task was effective in inducing perceived cognitive fatigue and that watching the documentary did not affect the perception of fatigue levels.

Influence of perceived CF on COP measures

Violin plots of the COP relative change scores are shown in Figs. 3 and 4. The results of the repeated-measures ANOVAs on the relative change scores are collected in Tables 1 and 2. No significant group effects were present for any of the three COP outcome measures. Moreover, *t* tests revealed that the relative change scores of the COP outcome measures did not differ significantly from a test value of zero, i.e., over all tasks in both directions (see Supplementary Tables 3, 4). The absence of significant main effects of posture and condition implies that the balance tasks were performed in a similar manner before and after the interventions.

Although no significant main effects occurred, a few weakly significant interaction effects were observed. Significant group x posture interaction effects were found for both sway variability and sample entropy using Lake et al.'s method in the ML direction, but not in the AP direction. These effects occurred because in the control group neither sway variability nor sample entropy changed due to the intervention in either posture, whereas in the experimental group a decrease of sway variability and an increase of sample entropy occurred in the hip-broad stance, but not in the tandem stance. Additionally, significant condition x group interactions were found for the relative change in sample entropy using Lake et al.'s settings in both sway directions. Post hoc tests revealed that in the eyes-closed condition sample entropy values were affected differently by the two interventions. Whereas the relative change in sample entropy was positive for the experimental group, indicating less regularity and greater automaticity, the relative change was negative for the control group, indicating greater regularity and less automaticity. These significant interactions were absent

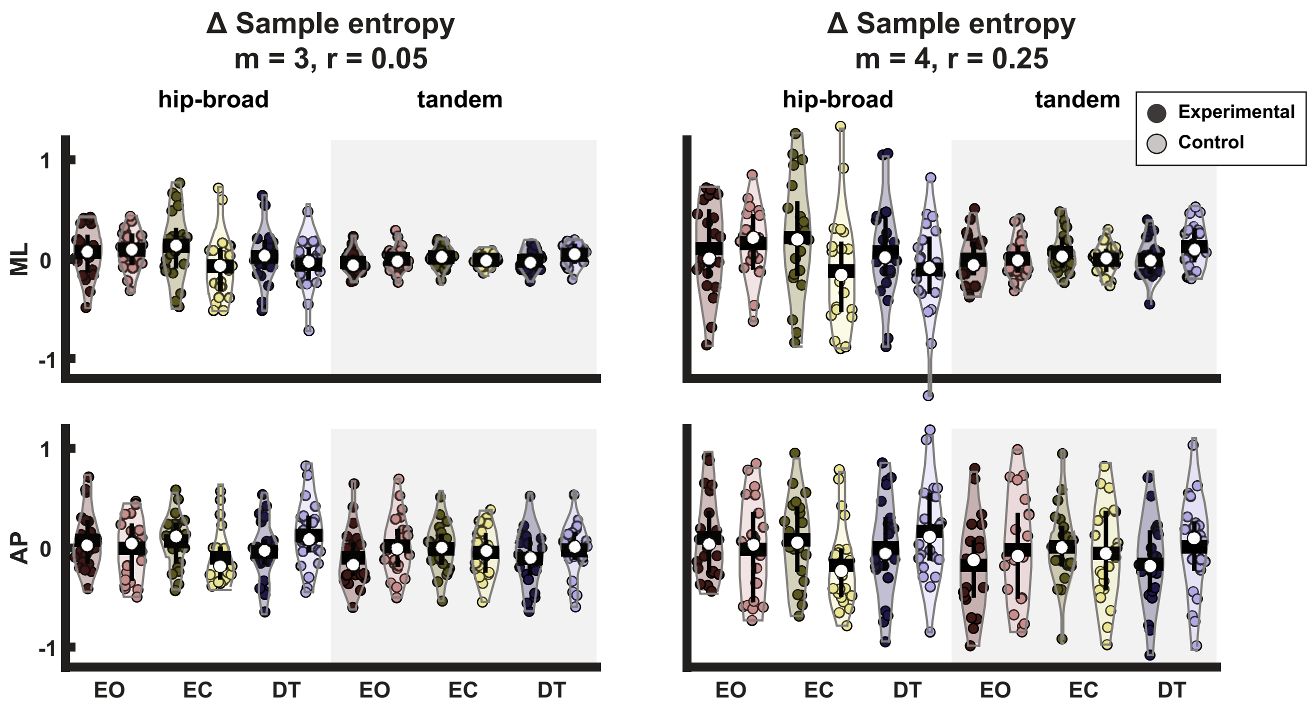


Fig. 4 Left panels: relative change of sample entropy, according to Lake et al.'s method; right panels: relative change of sample entropy according to Montesinos et al.'s method in ML (above) and AP (below) direction. Experimental group [dark colors], control group [light colors]. Each dot represents one participant, and the violin the spread of the data. Horizontal bar represents the mean; vertical bar represents the interquartile range, and the white center dot represents the median

Table 1 Statistical results of the repeated-measures ANOVA on the relative change of sway variability and mean speed values

Effects	Δ sway variability				Δ mean speed			
	df (1, 2)	*F*	*p*	η_p^2	*df* (1, 2)	*F*	*p*	η_p^2
Group								
ML	1.41	2.60	0.115	0.06	1.41	0.57	0.455	0.01
AP	1.41	0.23	0.637	0.01	1.41	2.01	0.164	0.05
Posture								
ML	1.41	1.44	0.238	0.03	1.41	0.36	0.553	0.01
AP	1.41	0.89	0.352	0.02	1.41	2.54	0.118	0.06
Condition								
ML	1.8, 75.8	0.20	0.803	0.01	1.7, 70.5	1.33	0.270	0.03
AP	2.0, 80.2	0.01	0.992	0.00	1.9, 76.2	1.52	0.225	0.04
Posture × group								
ML	1.41	5.23	**0.027**[a]	0.11	1.41	0.07	0.796	0.00
AP	1.41	1.82	0.185	0.04	1.41	0.20	0.657	0.01
Condition × group								
ML	1.8, 75.8	2.53	0.091	0.06	1.7, 70.5	1.90	0.163	0.04
AP	2.0, 80.2	0.01	0.203	0.04	1.9, 76.2	3.02	0.058	0.07
Posture × condition								
ML	1.9, 78.9	1.64	0.202	0.04	1.9, 79.2	0.99	0.357	0.02
AP	2.0, 80.6	0.61	0.546	0.02	1.8, 73.2	0.00	0.999	0.00
Posture × condition × group								
ML	1.9, 78.9	0.74	0.477	0.02	1.9, 79.2	2.28	0.111	0.05
AP	2.0, 80.6	0.69	0.503	0.02	1.8, 73.2	0.31	0.702	0.01

df degree of freedom

[a]Significant, $p < 0.05$

Table 2 Statistical results of the repeated-measures ANOVA on the relative change of sample entropy values; left: calculated using Lake et al.'s method; right: calculated using Montesinos et al.'s method

Effects	Δ Sample entropy: $m=3$, $r=0.05$				Δ Sample entropy: $m=4$, $r=0.25$			
	df (1, 2)	*F*	*p*	η_p^2	*df* (1, 2)	*F*	*p*	η_p^2
Group								
ML	1.41	1.09	0.304	0.03	1.41	1.38	0.247	0.03
AP	1.41	0.11	0.742	0.00	1.41	0.03	0.862	0.01
Posture								
ML	1.41	1.04	0.314	0.03	1.41	0.18	0.676	0.00
AP	1.41	3.05	0.088	0.07	1.41	2.00	0.165	0.05
Condition								
ML	1.8, 75.2	0.72	0.477	0.02	1.9, 76.2	0.39	0.671	0.01
AP	2.0, 80.9	0.08	0.918	0.00	2.0, 80.6	0.15	0.860	0.00
Posture × group								
ML	1.41	4.17	**0.048**[a]	0.09	1.41	3.35	0.075	0.08
AP	1.41	1.24	0.272	0.03	1.41	1.41	0.241	0.03
Condition × group								
ML	1.8, 75.2	3.28	**0.047**[a]	0.07	1.9, 76.2	2.66	0.078	0.06
AP	2.0, 80.9	3.77	**0.028**[a]	0.08	2.0, 80.6	2.95	0.059	0.07
Posture × condition								
ML	1.9, 76.9	1.78	0.178	0.04	1.9, 79.5	1.57	0.215	0.04
AP	1.9, 79.5	0.83	0.437	0.02	2.9, 77.0	1.24	0.293	0.03
Posture × condition × group								
ML	1.9, 76.9	0.79	0.451	0.02	1.9, 79.5	1.29	0.280	0.03
AP	1.9, 79.5	1.84	0.167	0.04	2.9, 77.0	0.53	0.578	0.01

df degree of freedom

[a]Significant, $p < 0.05$

when using Montesinos et al.'s method for calculating the sample entropy.

Discussion

This study was conducted to examine the effect of perceived CF on postural control during quiet standing in young adults. We ventured to do so in an encompassing manner to help resolve the existing ambiguity in pertinent studies. In line with the prevailing assumption in previous studies, we hypothesized that CF leads to a worsening of the ability to maintain quiet upright stance, resulting in increased COP sway variability and mean speed, and lower sample entropy values. Additionally, we hypothesized that the influence of CF on balance control depends on the attentional effort required by the balance tasks. To test these hypotheses, we included several static balance tasks that differed in difficulty and attentional demands.

COP behavior before intervention

We first verified that the six balance tasks varied in difficulty and attentional demands before the intervention by comparing the selected COP outcome measures across tasks. This was the case. The COP time series differed significantly between the two postures as well as between the three conditions in which these postures were maintained. The effect of posture on the three COP outcome measures was clear-cut and confirmed our expectation that standing in tandem stance is less stable than standing in hip-broad stance. Furthermore, post hoc analyses confirmed that standing with eyes closed is less stable than standing with eyes open, and that the introduction of a cognitive dual-task reduces attentional control over the balance task. Although not all post hoc comparisons between the balance conditions were significant for the three COP outcome measures, the significant effects were all in the expected direction. The effect of condition on the sample entropy was less pronounced than expected (e.g., sample entropy values were not significantly lower for standing with eyes closed compared to standing with eyes open).

Nevertheless, the obtained findings are in line with previous studies which have shown that: (i) a posture with a smaller base-of-support is more challenging (Sarabon et al. 2013; Lee and Shin 2019), (ii) postural control becomes more 'automatic' and efficient when attention is directed externally, i.e. with eyes open (Stins et al. 2009;

Potvin-Desrochers et al. 2017; Rhea et al. 2019; Richer and Lajoie 2020; Yamada and Raisbeck 2021) and less 'automatic' and efficient when attention is directed internally, i.e. with eyes closed (Donker et al. 2007; Stins et al. 2009; Becker and Hung 2020), and that cognitive tasks promote automatization of postural control in young and older adults (Donker et al. 2007).

Importantly, the analysis of the COP behavior before intervention not only showed that the balance task manipulation was effective, but also that no significant difference existed between the groups, implying that any significant group difference in COP behavior after the intervention could be attributed to the intervention.

Sleep quantity and quality

We verified that no significant differences existed in the quantity and quality of sleep of the two groups before the intervention since such differences might confound the results. Therefore, we also verified that no significant differences existed in the quantity and quality of sleep of the experimental group before the extra session and before the intervertion. Hence, any group effect due to difference in sleep could be ruled out.

Levels of perceived cognitive fatigue

Finally, we verified that the method we used to induce fatigue was effective and led to significantly higher levels of perceived cognitive fatigue than watching a documentary. The experimental group reported significantly higher levels of perceived CF after performing the TloadDback task, compared to the control group. Furthermore, the individualized TloadDback task led to comparable levels of perceived CF reported by the participants of the experimental group, as indicated by the small between-subject variance (Borragan et al. 2017). In contrast, the variation of perceived CF levels after the intervention reported by the control group was considerable (see Fig. 2, left). However, when participants were asked to reflect about the change in their perceived CF level, by comparing their CF status before and after the intervention, the control group reported no change in CF (see Fig. 2, right). One explanation of this paradoxical finding is that perveiced CF levels of the control subjects were already broadly distributed before the intervention and left unaffected by watching the documentary. However, this is impossible to verify as we deliberately refrained from assessing perceived levels of CF before the intervention. Another explanation is that the broad variation in post-intervention CF ratings is a genuine reflection of how the control participants felt after the documentary but did not relate to how they felt before. The verbal feedback provided by the control participants after the experiment speaks in favor of this second explanation: some described the documentary as 'boring', some said it made them feel 'relaxed' or 'sleepy', while others qualified the documentary as 'interesting' and 'stimulating'. This illustrates that finding an adequate control intervention is difficult. Finally, the choice of the documentary was based on comparable studies by Hachard et al. (2020) and Varas-Diaz et al. (2020), but like any other documentary, may well have the drawback that participants perceive it differently.

Influence of perceived cognitive fatigue on postural control

Our main hypotheses were disconfirmed: no significant main effects of group were found in any of the COP measures, indicating that perceived CF, although clearly present in the experimental group, had no statistically discernable effect on static balance control. In the absence of a main effect of group, also the hypothesis that the influence of CF on balance control depends on the attentional effort required by the balance tasks was generally disconfirmed. The only statistical evidence found in favor of this hypothesis were a few weakly significant interaction effects involving the factor group. A significant posture x group interaction effect was found in the ML-direction for the relative change in sway variability and sample entropy when calculated according to Lake et al.'s method, but not when calculated according to Montesinos et al.'s method. This effect occurred because CF affected postural control in the ML direction in hip-broad stance, but not in tandem stance. This finding precludes a clear interpretation, since an effect on tandem stance rather than hip-broad stance would have been expected, assuming CF hampers balance control through depletion of cognitive resources. Additionally, significant condition x group interactions were found for the relative change in sample entropy when calculated according to Lake et al.'s method, but not when calculated according to Montesinos et al.'s method. These effects occurred because the relative change score of sample entropy was positive in the eyes-closed condition in the experimental group and negative in the control group and could thus at least partly be interpreted in terms of a depletion of cognitive resources (resulting in less attentional control and thus less regularity and greater automaticity). However, this finding was non-robust as it proved to be critically dependent on the precise settings for calculating sample entropy. Collectively, these results suggest that, in young adults, postural control in static balance tasks is largely automatic and only marginally affected by CF.

One could argue that the level of CF was not severe enough, even though participants in the experimental group indicated clearly that they felt more fatigued after the intervention. Whereas Borragan et al. (2017) and O'Keeffe et al. (2019) showed that performing the TloadDback task for its standardized duration of 16 min is sufficient to cognitively fatigue participants, Jacquet et al. (2020) argued that this is too short to affect physical performance. According to them, performing a cognitively fatiguing task for such a short duration intervenes primarily with people's perception of fatigue, rather than inducing sufficient CF to reduce their motor abilities. Pitts and Bhatt (2023) raised a similar concern. Although this concern is valid, it should not be used to dismiss any null finding as invalid, certainly not in situations, such as in the present study, where the attentional component of balance control is expected to be small. Deschamps et al. (2013) and Hachard et al. (2020) used cognitively fatiguing tasks of 30- and 90-min duration, respectively, but also found no (or no strong) effects of CF. Deschamps et al. (2013) found no effects of CF while standing on a stable surface with eyes open or closed; only while standing on an unstable surface, the effects of CF became manifest. They not only found a reduced efficiency of postural control in different conditions in the experimental group, but also in the control group. It therefore seems that the observed changes in postural control did not result from the experimentally induced CF, but from some confounding variable (e.g., sitting). A significant effect on postural control between the experimental and control group was only observed during standing with eyes closed on a stable surface. The results of Deschamps et al. (2013) and Hachard et al. (2020) thus indicate that the effect of CF on postural control does not become stronger or more obvious for longer durations of the cognitively fatiguing task.

Since no consistent effects of CF on postural control were found across studies, it might be that, in healthy young adults, static balance does not require sufficient attentional resources to be significantly affected by the cognitive resource depletion resulting from CF. Despite the evidence that even simple static balance tasks require investment of attentional resources, maintaining postural stability during unperturbed upright standing is widely regarded as a largely automatic and reflex-based process, which demands only very little attention (Kerr et al. 1985; Teasdale et al. 1993). This line of thinking is supported by the observation that older adults seem more sensitive to CF. In a study by Varas-Diaz et al. (2020), with a design similar to our study, significant impacts of CF in healthy older adults as well as people who had suffered a stroke were observed. Postural control was found to be impaired under various sensory conditions and when concurrently performing a cognitive task. These enhanced effects of CF might derive from the fact that attentional demands to maintain equilibrium during static balance tasks increase with aging and pathological conditions (Teasdale et al. 1993; Bisson et al. 2011). In contrast to healthy young adults for whom the performance of simple static balance tasks seems effortless, neurodegenerative processes reduce postural control in older adults, rendering balance maintenance more difficult (Bergamin et al. 2014). This is reflected in increased sway and decreased sample entropy values (Roerdink et al. 2006). Apart from physical changes, the increased effort for postural control can also be explained by reduced cognitive functions (Amboni et al. 2013). We conclude that the chosen postural tasks in this experiment required too little attention and effort such that the evoked depletion of cognitive resources did not interfere with postural control in our sample of healthy young adults.

Future studies assessing whether (and if so, which) postural parameters are affected by CF should either make the postural tasks more challenging and thus attention demanding (Lew and Qu 2014), or intensify the level of induced CF, which might be achieved by sleep deprivation (Patel et al. 2008; Cheng et al. 2018; Batuk et al. 2020).

Strengths and limitations

The study has two main strengths. First, our study was well powered, rendering its results robust and meaningful. Second, the inter-individual variation in the level of induced CF was minimized by individualizing the stimulus duration time of the TloadDback task. The study also has three main limitations. First, because the level of CF induced by the intervention was rated only subjectively, it cannot be ruled out that the subjective ratings were influenced by other confounding factors, such as perceptual, memory, and affective processes. In future studies, including questions about boredom, motivation, and sleepiness might help tease out whether those factors influence the levels of perceived cognitive fatigue. Second, and relatedly, the absolute and relative subjective ratings of CF by the control group were paradoxical and not readily interpretable, rendering it not fully certain that watching the documentary induced no CF whatsoever. Third, since cognitive fatigue is highly subjective, a within-group design might have been more appropriate. However, we found a clear effect of the intervention so the main advantage of having a within-group design compared to a between-group design, the higher power, was not necessary.

Conclusion

Based on the premise that cognitive, attentional control plays a significant role in the performance of balance tasks, it is often assumed that cognitive fatigue impedes balance by depleting cognitive resources. However, in healthy young adults the influence of cognitive fatigue and the associated depletion of cognitive resources on the performance of static balance tasks is marginal at best. In this population and task domain, postural control is largely automatic with minimal cognitive mediation.

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Data availability To allow reproducibility of our results and any further analyses all data and code can be found at: https://osf.io/jatc6/.

Declarations

Conflict of interest None of the authors report any conflict of interest.

Consent to participate All participants signed an informed consent form prior to the experiment.

Ethical approval This study was approved by the local ethics committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE-2022-154R2) and the protocol fully complied with the Declarations of Helsinki.

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