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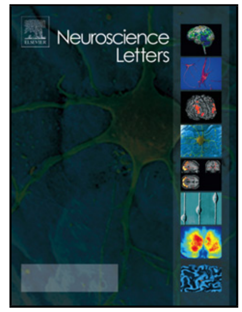

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Sway regularity and sway activity in older adults' upright stance are differentially affected by dual task

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Research highlights

- Dual-task effects on sway regularity and sway activity were examined in older adults.
- Sway entropy and sway activity were positively related under dual-task conditions.
- Increased sway activity in dual task was associated with increased sway irregularity.
- Postural stability is determined by ability to allocate attention to balance task.

Abstract

Age-related changes in postural control are attributed to visual, vestibular and proprioceptive dysfunctions, muscle weakness, and reduced availability of neural resources required for efficient balance control. Concurrent performance of complex cognitive tasks while standing or walking is expected to increase balance instability due to under-recruitment of brain resources and insufficient allocation of attention to the postural task. Both balance instability and attentional control of movements can, nonetheless, be determined from the center of pressure (CoP) measurements by examining the effects of dual-task on the amount of sway activity (as measured by CoP velocity - Vcop) and the statistical regularity of the CoP trajectory (the wavelet entropy of the signal - WEcop). The abovementioned characteristics were examined in the present study in a group of 13 healthy older adults. The task involved maintaining Romberg stance for 25 s with or without performing an attention demanding cognitive tasks (word memorization or mathematical counting). A linear mixed-model study was designed to analyze the extent to which sway activity can predict sway regularity. Findings from the present study showed that, on average, Vcop and WEcop were positively correlated ($p = 0.014$), suggesting that older individuals who exhibited greater amounts of sway (i.e., higher Vcop) also increased sway irregularity of the posturogram - as evidenced by a higher level of wavelet entropy of the CoP trajectory. Nevertheless, results of the linear mixed model showed that significant positive associations between Vcop and WEcop were found only in dual task ($R \geq 0.67$, $p \leq 0.012$). Furthermore, dual-task effects (% change in performance) on both sway characteristics were not significant ($p > 0.1$), suggesting that none of the attention demanding cognitive tasks used in the present study was sufficient to divert a critical amount of attentional resources from the postural task. Finally, performance of the mathematical counting (but not the word memorization) task was deteriorated from sitting to standing, however this effect was marginal ($p = 0.075$). Taken together, we proposed that while dual task could hinder balance control, postural stability may still be maintained by allocating more attentional resources to the postural task and reducing automatized control.

Key words: aging, balance control, attention, dual-task, entropy

1. Introduction

Balance stability is fundamental in humans at all ages, but becomes increasingly critical with aging [1]. The negative effect of age on balance stability is attributed primarily to sensorimotor dysfunctions [2,3], muscle weakness [4], and structural changes in brain grey and white matter [5,6]. However, evidence from other studies suggest that, despite the abovementioned neural deficits, older adults may recruit additional neural resources to reach sufficient level of sensorimotor control by increasing attention to the task ahead [7,8-11]; for review see [12]. Since availability of attentional resources and the ability to allocate attention efficiently is declining with aging [7,12-14], allocation of attentional resources toward a secondary cognitive task is expected to have a larger interference effect on balance in older adults than in young adults [15-19]; for review see [20]. This makes dual-task testing a sensitive predictor of age-or pathology-associated declines in balance control [16,21].

Measurements of center of pressure (CoP) excursions during quiet standing are taken commonly as an index of postural stability during performance of static or dynamic balance tests [5,6,15,17,22-24]. From a biomechanical perspective, CoP provides a first approximation to the location of the body's center of mass over the standing surface, with increased CoP fluctuations taken as a sign of poor balance control. However, older adults often tend to increase conscious control of balance by allocating additional attentional resources to the postural task [15-19,24] rather than relay on automatic postural adjustments; presumably as a compensatory strategy for decrements in ankle proprioception control [2]. Importantly, the automaticity of postural control can be quantified by statistical regularity of the CoP trajectory quantified by the entropy of the CoP signal [23-25]. Hence, CoP regularity could be used for indexing the amount of attention invested in the postural task [24]. Accordingly, we suggested that CoP regularity might serve as a better indicator of cognitive-motor interference in balance control than CoP displacement and speed characteristics [25]. Specifically, we hypothesized that, as compared to the conventional properties of CoP sway (e.g. CoP sway velocity or CoP area), properties of CoP regularity: *(i)* would be affected by dual-task to a larger extent, and *(ii)* would be more sensitive to the type of cognitive interference. The abovementioned hypotheses will be examined in a group of healthy older adults as this population is expected to be more vulnerable for cognitive interferences than their younger counterparts, allowing better definition of the interface between postural control and cognition.

Finally, associations between sway activity and sway regularity have been examined. While diversity in the amount of CoP displacement and/or speed is expected to reflect individual differences in system integrity (e.g., poor proprioception), changes in regularity scores (as manifested by an increase or decrease in CoP entropy) are expected to be associated with more/less successful deployment of attention to the postural task [23,24]. Along this line of thinking, we could expect significant negative associations between measures of system regularity and sway activity if lower sway regularity (i.e., high entropy) and poor recruitment of attentional resources give rise to higher postural instability (high sway activity). Alternatively, poor balance control (i.e., higher sway activity) may result in higher sway regularity (low entropy) and reduced allocation of neural resource to the cognitive task as a compensatory mechanisms, giving rise to significant positive correlation between sway entropy and sway activity. Both possibilities could be true as the interplay between sway activity and sway regularity may largely be determined by task prioritization. For example, some individuals may still shift their attention from the balance control task to the cognitive task to gain better cognitive performance scores but shift back to the balance control task when sway activity becomes too large; possibly giving rise to significant negative correlation between sway entropy and sway activity. Yet again, it is more than likely that older participants will prioritize the balance control task over the cognitive task [24]. Therefore, a significant positive correlation between sway entropy and sway activity is predicted to be more predominant than a significant negative correlation.

2. Methods

2.1 Participants

Participants were 13 older healthy human males (Mean age: 70.6±5.8 years; Mean height: 173.8±5.8 cm; Mean weight: 81.2±8.8 kg; Mean BMI: 26.8±2.1 kg/m^2). Participants were asked to complete a questionnaire about their demographic data, physical activity habits, and health status prior to their inclusion in the study. All participants were free of any physical and/or neurological disorders and were screened for cognitive impairment with the Mini–Mental State Examination test using the cut-off score of 24. Participants did not report using any medications or drugs that could act on the nervous system and/or affect motor/cognitive functions; were free of chronic pain and did not experience any pain during data collection. Participants who reported the consumption of medications for blood pressure control were included in the study. All participants were tested at the same time of the day between 9-10 a.m. Participants were naïve about the purpose of the study but were informed that testing would involve examination of their postural control stability and will include memory tests. All participants signed inform consent form before their inclusion in the study. Research was conducted at the Lithuanian Sports University, Institute of Sport Science and Innovations. The study was approved by the Kaunas Regional Biomedical Research Ethics Committee (License No. BE-2-46).

2.2. Procedure

A posturography method with a single piezoelectric force plate (KISTLER, Switzerland, Slimline System 9286) was used to measure postural sway activity. The signals collected from the force plate were sampled at 100 Hz and were stored on PC for an off-line analysis. The application point (center of pressure - CoP) of the measured foot-ground reaction forces in the anteroposterior (AP) and mediolateral (ML) directions was calculated based on the known geometric locations of the piezoelectric transducers. Participants were instructed to step, barefoot, on the force plate and to stand still in a Romberg stance position with eyes open. The positioning of the feet was similar for all subjects and participants were instructed to place their feet along the midline of the platform. CoP recordings were made under three experimental conditions: *(i)* Romberg stance as a single task (RO-S), *(ii)* Romberg stance while performing a Word Memory task (RO-WM), and *(iii)* Romberg stance while performing a Mathematical Counting task (RO-MC). Each participant performed each condition four times, resulting in a total of 12 trials per participant. The trials were presented in random order. For each trial, participants were asked to stand on the platform for 25 seconds for which data were collected over a period of the last 20 seconds. The 5 first seconds prior to data collection were used to allowed participants to accommodate to the required standing position. All participants were allowed to practice the Romberg stance prior to data collection.

For the Word Memory task, an audiotape played previously recorded ten words (Lithuanian nouns) in each trial. Trail length was 20s and words were introduced every 2s. Participants were instructed to concentrate on words and to memorize as many words as possible. At the end of each trial participants were asked to verbally report the words that they memorized. For the Mathematical Counting task, negative or positive one-digit integernumbers (10 in total) were presented vocally in each trial at 2 second intervals and participants were instructed to calculate and remember the sum of the played numbers. For example, the correct answer “10” was expected for the numbers [+6, +8, -3, +9, -5, -1, +6, -8, -4, 2]. Participants were instructed to concentrate on the calculation and to memorize the calculated sum in their mind at each step throughout the trial. At the end of each trial participants were asked to verbally report the correct answer. Participants were familiarized with the two cognitive tasks before the start of the experiment. Following familiarization, participants were instructed to perform 4 trials of the Word Memory task and 4 trials of the Mathematical Counting task while seated (i.e., cognitive single task); 2 trials were performed at the beginning (i.e., prior to the performance of the 12 posturographic conditions) and 2 trials at the end of the main body of data collection. For the Word Memory task, the number of missed words in each trial was obtained and averaged for the four trials. Performance measures for the Mathematical Counting task were taken as the amount of correct and incorrect answers in each task condition.

2.3 Data processing and statistics

Prior to all analyses, mean and linear trends of the AP and ML components of the CoP trajectory were subtracted and spectral analysis was performed to determine the frequency characteristics of the raw signals. Since 99% of the overall power of the signals was below 15 Hz and contribution of higher frequencies was nearly zero, a fourth-order low pass Butterworth bi-directional filter with a cutoff frequency of 15 Hz was applied. To estimate the dynamical characteristics of the posturogram, CoP velocity vector (Vcop) and wavelet entropy (WEcop) [26] were calculated from the displacement vector of the CoP. The Vcop is refers to the amount of sway activity and appears as a conventional, scale-dependent characteristic of the posturogram. The WEcop, on the other hand, is a scale-independent measure that quantifies the degree of order/disorder of the signal; therefore providing information about the regularity of the posturogram. Specifically, wavelet entropy is defined according to the distribution of energy in a wavelet frequency band. A focused energy distribution corresponds to small wavelet entropy (i.e. all relative wavelet energies will be almost zero except for the wavelet resolution level which includes the representative signal frequency). In contrast, a smooth energy distribution has large wavelet entropy since it is expected to consist of a wavelet representation with significant contributions from all frequency bands. To avoid a boundary effect a Hamming window was applied for WEcop calculation. The algorithms used for calculating the Vcop and WEcop were obtained by using custom-written MATLAB scripts (MathWorks, Natick, MA).

The posturographic dependent variables Vcop and WEcop were averaged over the four repeated trials in each of the three task conditions: single-task Romberg stance (RO-S), dual-task Romberg stance with Word Memory task (RO-WM), and dual-task Romberg stance with Mathematical Counting task (RO-MC). Nonparametric statistics was used for non-normally distributed data. Whenever appropriate, the Wilcoxon test was used for pair wise comparisons. The analysis of variance (ANOVA) for repeated measures was performed on posturographic data that follow normal distribution. In line with our first research questions, we compared *(i)* sway activity and sway regularity of the posturogram as function of task (i.e., single-task, dual-task Word Memory, dual-task Mathematical Counting), *(ii)* differences in performance of the cognitive Word Memory task and the Mathematical Counting task in single-task (i.e., in seated position) and dual-task conditions (i.e., during Romberg stance), and *(iii)* the dual-task effect (DTE) on sway activity, sway regularity, Word Memory, and Mathematical Counting. For all variables, negative DTE values indicate deteriorated performance in dual-task (i.e., dual task cost), whereas positive values represent an improvement in dual-task with respect to single-task (i.e., dual task benefit).

In line with our second research question, a repeated measure ANOVA with a time-varying covariate was performed on the data acquired in all trials to examine the effects of sway activity (as assessed by Vcop) on sway regularity (as assessed by WEcop). Again, WEcop data were examined across the reference state (i.e., the RO-S task) and two motor-cognitive interference states (i.e., the RO-WM and the RO-MC tasks) and the outcome was conditioned on the time varying covariate Vcop, using a linear mixed model analysis. The model was designed to evaluate the random effects of Vcop and conditions on WEcop, assuming that Vcop can take on a different value for each of the three repeated observations. All statistical analyses were performed with SPSS for Windows software (version 20.0). For all data, arithmetic means and standard deviation were calculated. The level of significance was set at $p < .05$.

3. Results

3.1 Posturographic measures

Group means (± SD) of the two dependent posturographic measures (Vcop and WEcop) at single-task (RO-S) and dual-task (RO-WM, RO-MC) and dual-task effects (DTE) are summarized in Table1. The statistical analyses revealed no significant effect of dual task on either Vcop [Friedman ANOVA χ^2 (13,2) = 4.31, p = 0.105] or WEcop [Friedman ANOVA χ^2 (13,2) = 0.51, p > 0.9]. Examination of the individual data showed different patterns of dual-task interference effects between the two dual task conditions. Dual-task interferences on postural sway (Vcop) were evident mainly in the RO-WM condition (8 of 13 individuals increased Vcop during dual-task) than in the RO-MC condition (only 3 of 13 individuals increased Vcop during dual-task whereas 10 of 13 showed a decrease in Vcop). However, DTE on sway activity for the RO-WM and RO-MC conditions were not significantly different (Wilcoxon Z(13) = 1.22, p = 0.22); see illustration Figure 1A.

For regularity of the posturogram (WEcop), 8 of 13 individuals showed lower WEcop levels (higher regularity) in the RO-WM condition and 7 of 13 individuals showed lower WEcop in the RO-MC condition (whereas the remaining individuals showed the opposite trend). Again, DTE differences on sway regularity between the two task conditions was not significant (Wilcoxon $Z(13) = 1.36$, $p = 0.17$). Interestingly, decreased regularity of CoP from RO-S to RO-WM standing was associated with increased regularity of CoP from RO-S to RO-MC, as expressed by the negative DTE scores on sway regularity for the RO-WM and the positive DTE scores on sway regularity for the RO-MC; see illustration Figure 1A. Regression analyses were applied to verify possible associations between performance interferences to sway activity and sway regularity in the RO-WM and RO-MC conditions. However, no significant correlations were found [Vcop: Spearman $R = -0.06$, $p > 0.8$; WEcop: Spearman $R = -0.52$, $p = 0.067$); see illustration Figure 1B.

3.2 Associations between WEcop and Vcop

The results of linear mixed model revealed a significant effect of the Vcop on WEcop as function of task ($p = 0.014$), indicating that, on average, higher regularity (i.e., lower WEcop) was associated with lower sway activity (i.e., lower Vcop). However, significant fixed effects of sway activity on CoP regularity varied across conditions. Specifically, significant positive correlations between Vcop and WEcop were evident in the two dual task conditions [RO-WM: $R = 0.69$, $p = 0.010$; RO-MC: $R = 0.67$, $p = 0.012$) but not in single task (RO-S: $R = 0.17$, $p > 0.5$); for illustration see Figure 1C.

Table 1 & Figure 1 about here

3.3 Cognitive measures

Group means (± SD) of the measures of cognitive performance and the dual-task interference effect (DTE) on cognitive task performance are presented in Table 2 for the two cognitive tasks (for illustrations, see Figure 2). For the Mathematical Counting task, changes in the number of correct and incorrect answers were found at a borderline level of statistical significance [Wilcoxon $Z(13) = 1.78$, $p = 0.075$], with participants making more correct answers in the seated compared with the RO-MC standing condition. No change in the amount of word repeating mistakes was found for the Word Memory task [Wilcoxon $Z(13) = 0.07$, $p > 0.9$]. Finally, regression analysis was applied to examine possible associations between performance scores and dual task effects on the two cognitive task. However, no significant correlations were found [all Spearman $|R| \leq 0.39$, $p \geq 0.18$].

Table 2 & Figure 2 about here

4. Discussion

The results of the present study indicated that dual-task effects on sway activity and sway regularity were not significant for either of the two cognitive tasks. Nevertheless, observations from the mixed-model analyses indicated that the sway entropy and sway activity were positively related to each other and that significant association between the two abovementioned outcome measures was evident under the two dual-task conditions. Specifically, older individuals who exhibited greater amounts of postural sway (i.e., higher Vcop) also demonstrated lower levels of sway regularity (i.e., higher entropy), suggesting that their balance control was somewhat more automatized than individuals who showed lower amount of sway. In line with evidence from other studies, lower sway regularity is explained by poorer capacity to recruit sufficient attentional resources to manage two tasks [23-25]. As such, our observations are consistent with the assumption that participants who showed greater amount of postural sway did not have sufficient attentional resources to allocate to the postural task. However, there was no further evidence in our study to support this assumption, given the fact that no significant correlations were found between postural and cognitive performance measures; neither for the RO-MC task nor for the RO-WM task.

Mathematical Counting and Word Memory tasks may rely on activation of the same functional brain networks, however evidence shows recruitment of additional brain regions during performance of arithmetic task as compared with brain activation seen during retrieval of information [27]. Therefore, we expected to find more dual-task interferences during performance of the RO-MC than during RO-WM since processing capacity in the former may no longer be sufficient to support the two tasks due to the demands of the cognitive task [27-29]. Our observations partly confirm this supposition by showing that the amount of correct answers decreased when the postural task was performed together with Mathematics Counting (but not with Word Memory) as compared to the performance of the same task in seated position. Yet again, there were no statistical differences in performance of the postural task. On the basis of this finding, we can conclude that none of the cognitive tasks used in the present study was sufficient to divert a critical amount of attentional resources form the postural task. Interestingly, we found a negative association between dual-task effects of the two cognitive task on sway regularity (but not sway activity), suggesting that increased sway regularity in the RO-MC condition (i.e., when Mathematical Counting was applied during Romberg stance) was associated with decreased sway regularity in the RO-WM condition (i.e., when the word memory task was deployed) and the other way around. This association was not observed for the sway activity outcome measure (Fig. 1B), suggesting that sway regularity was more susceptible to dual-task effects than sway activity. The significant positive correlation between Vcop and WEcop found for both dual-task conditions (Fig. 1C) suggests, however, that participants were able to reduce dual-task interference by increasing attentional control irrespective of the cognitive task involved [15-19, 28, 29].

To conclude, we suggest that the two cognitive interference tasks used in this study have a differential impact on attentional requirements and deployment of attention between postural and cognitive tasks. Yet, our findings also indicate that the ability to maintain postural stability would largely be determined by variability in the capacity of older adults to recruit attentional resources and allocate attention to the balance task. Further research should examine whether withdrawal of attention from the balance task could account for unpredicted falls in individuals with impaired postural control.

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Table 1: Group means (± SD) of the posturographic outcome measures and dual task effect (DTE) (% change in performance) on sway characteristics (Vcop and WEcop). Note: negative DTE scores indicate deteriorated performance whereas positive dual task effect scores indicate improved performance relative to performance of the single task.

	RO-S	RO-MC	RO-WM	DTE RO-MC (%)	DTE RO-WM (%)
Vcop (mm/s)	33.7 (6.9)	33.9 (6.3)	31.9 (8.6)	-2.66 (19.3)	6.10 (13.9)
WEcop (arbitrarry)	0.45 (0.07)	0.47 (0.08)	0.45 (0.08)	4.87 (14.4)	-5.3 (15.1)

RO-S = Romberg stance with no cognitive interference (single-task). RO-MC = Romberg task while performing Mathematical Counting. RO-WM = Romberg task while performing Word Memory.

Table 2: Group means (± SD) of the cognitive performance measures (number of mistakes) and dual task effect (DTE) (% change in performance) on cognitive task performance. Note: negative DTE scores indicate deteriorated performance whereas positive dual task effect scores indicate improved performance relative to performance of the single task.

	ST	DT	DTE (%)
Mathematical Counting	0.46 (0.66)	1.23 (1.36)†	-19.2 (35.6)
Word Memory	5.50 (1.32)	5.45 (0.82)	-3.47 (24.0)

†DT versus ST: $p = 0.075$ (Wilcoxon test); ST = single task. DT = dual task.

Figure Captions

Figure 1. Posturographic outcome measures and dual task effects on performance of the Romberg test. **(A)** Dual task effect on sway activity (Vcop) and sway regularity (WEcop) as function of the two cognitive tasks. (B) Associations between dual-task effects on the posturographic outcome measures. (C) Associations between the posturographic outcome measures in single task and the two cognitive conditions. RO-S = Romberg stance with no cognitive interference (single-task). RO-MC = Romberg task while performing Mathematical Counting. RO-WM = Romberg task while performing Word Memory. Note: negative dual task effect scores indicate deteriorated performance whereas positive dual task effect scores indicate improved performance relative to performance of the single task.

Figure 2. Cognitive outcome measures (A) and dual task effects on performance of the cognitive outcome measures (B). ST = single task. DT = dual task. MC = Mathematical Counting. WM = Word Memory. Note: negative dual task effect scores indicate deteriorated performance whereas positive dual task effect scores indicate improved performance relative to performance of the single task.

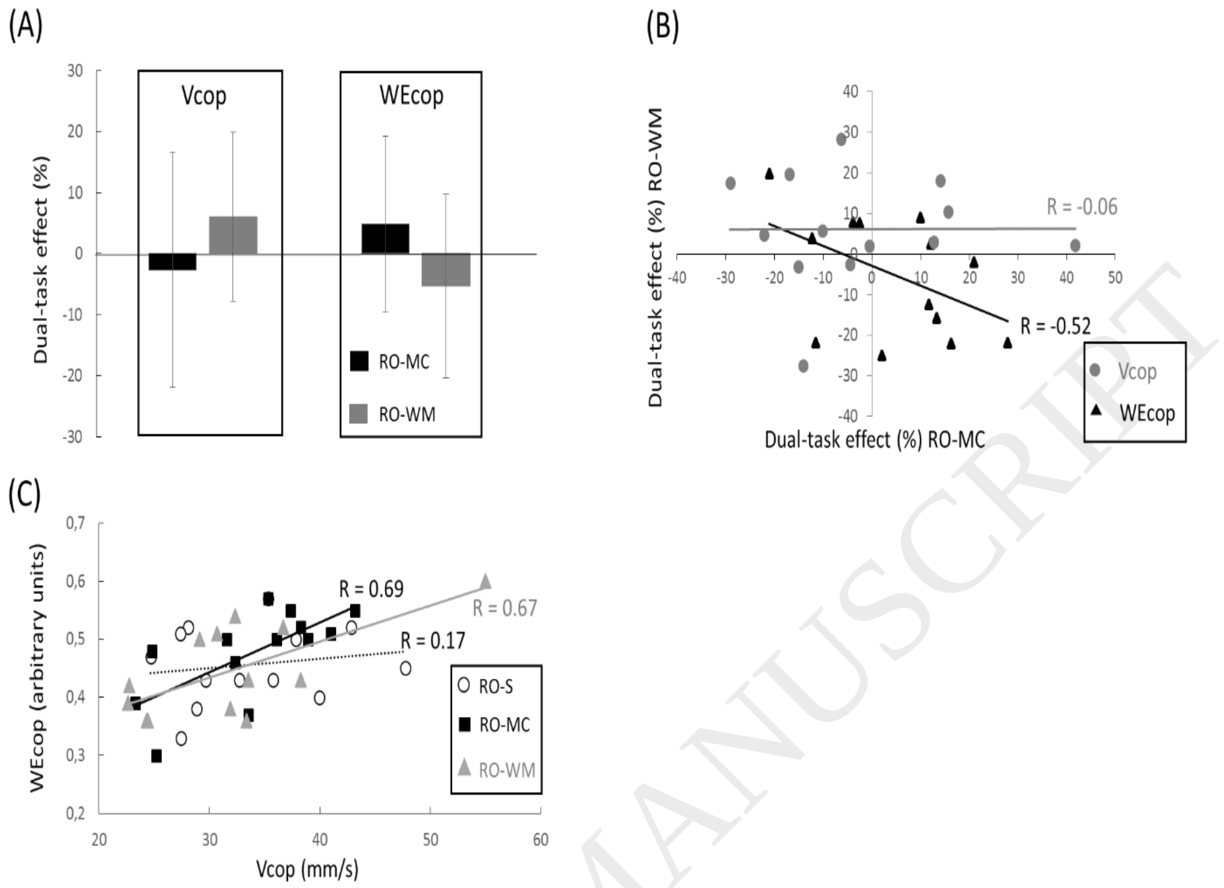
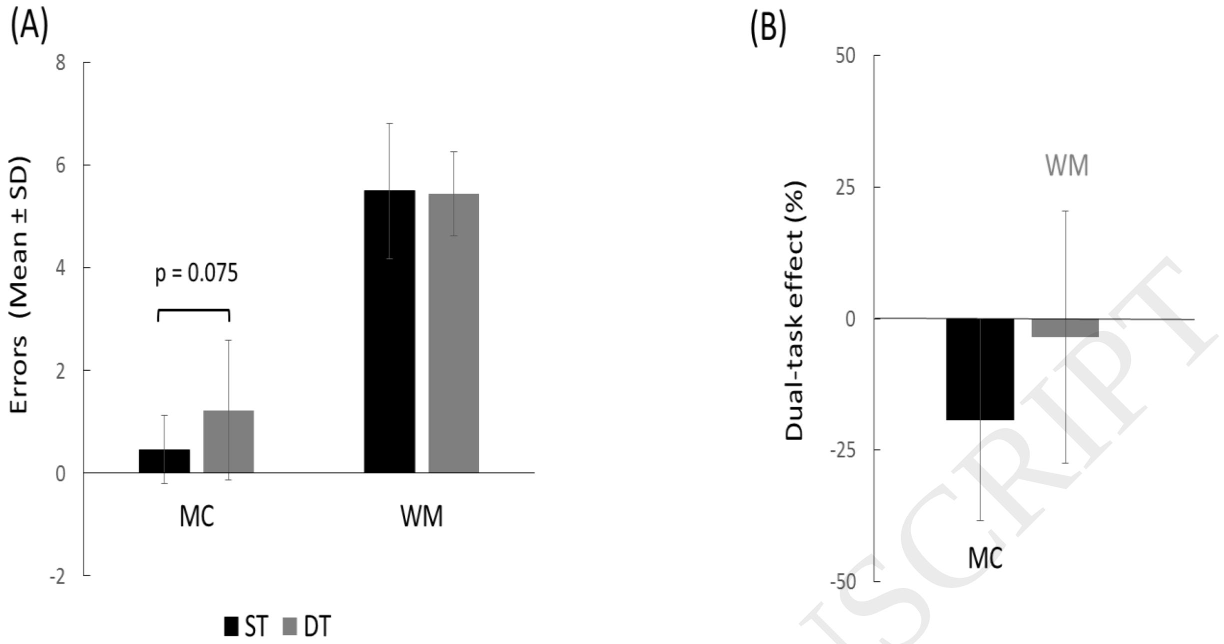


Figure 1. Posturographic outcome measures and dual task effects on performance of the Romberg test. (A) Dual task effect on sway activity (Vcop) and sway regularity (WEcop) as function of the two cognitive tasks. (B) Associations between dual-task effects on the posturographic outcome measures. (C) Associations between the posturographic outcome measures in single task and the two cognitive conditions. RO-S = Romberg stance with no cognitive interference (single-task). RO-MC = Romberg task while performing Mathematical Counting. RO-WM = Romberg task while performing Word Memory. Note: negative dual task effect scores indicate deteriorated performance whereas positive dual task effect scores indicate improved performance relative to performance of the single task.



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