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Balance capacity influences the effects of conscious movement processing on postural control in older adults

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A B S T R A C T

Older adults rely increasingly on conscious processes to control balance. While this could be in response to age-related declines in balance capacity, it is unclear whether such strategy is adaptive or not. We investigated whether balance capacity modified the effects of conscious movement processing (CMP) on postural control in older adults. Forty-seven older adults (M_{age} = 74.8, range = 61–88) completed 60-s, narrow-stance balance trials on a force platform, under conditions designed to increase (high-CMP; through movement-monitoring instructions) or reduce conscious processing (low-CMP; distraction task). Balance capacity was operationalised as a composite score of Berg Balance Scale and Timed-up-and-Go. Balance capacity influenced the effects of the CMP manipulation on mediolateral sway amplitude (p = .023). Specifically, it positively associated with sway amplitude during the high-CMP condition (β = 0.273), but not low-CMP condition (β = −0.060). In other words, higher balance capacity was associated with increased sway during high-CMP, confirming our hypothesis that CMP does not uniformly negatively impact balance performance. Rather, CMP was maladaptive for those with better balance. Results also indicated that older adults' balance capacity influenced the degree to which they could engage conscious or automatic postural control processes. Specifically, we found that, overall, participants showed reduced mediolateral sway frequency and complexity for the high-CMP vs. low-CMP condition (p's $\leq$ 0.018), indicating reduced automaticity of balance (as expected). However, these effects were significantly attenuated as balance capacity reduced (i.e., smaller changes in those with lower balance capacity, p's $<$ 0.010). Hence, the ability to readily shift between conscious and automatic modes of postural control seems more constrained as balance becomes worse. Overall, these findings suggest clinicians need to consider older adults' balance capacity when using providing instructions or feedback likely to influence CMP within rehabilitation settings.

1. Introduction

In the context of aging and neurorehabilitation, textbooks typically recommend minimising conscious involvement in balance (e.g.,

Abbreviations: CMP, conscious movement processing; COP, centre of pressure; MPF, mean power frequency; MSRS, movement-specific reinvestment scale; RMS, root-mean-square; SDA, stabilogram diffusion analysis; SEn, sample entropy.

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Rogers, Martinez, McCombe Waller, & Gray, 2014; Selzer, Clarke, Cohen, Kwakkel, & Miller, 2014). Supporting this idea, several studies have reported that conditions that limit the degree to which older adults consciously process their balance may promote greater postural stability (Chiviacowsky, Wulf, & Wally, 2010; Polskaia, Richer, Dionne, & Lajoie, 2015). These effects are in line with those of numerous studies in healthy young (sports) populations, which have consistently found conscious movement processing (CMP) to result in suboptimal motor performance in a range of different motor tasks (Masters & Maxwell, 2008; Wulf, 2013). Typically, these findings are interpreted as conscious processes 'constraining', and thus interfering in, automatic lower-level processes through which well-learned movement is typically regulated (Kal, van der Kamp, & Houdijk, 2013; Wulf & McNevin, 2001).

With aging, older adults often demonstrate an increased reliance on conscious processing to control balance (Boisgontier et al., 2013). However, rather than being detrimental to postural control per se, increased conscious processing can also be an adaptive response to age-related decline in balance capacity (Boisgontier et al., 2013; Huxhold, Li, Schmiedek, & Lindenberger, 2006). Indeed, in healthy young (sports) populations, CMP has been found to benefit low-skilled performers (who lack movement automaticity), whereas minimising conscious processing is most beneficial for skilled performers (Beilock, Carr, MacMahon, & Starkes, 2002; Castaneda & Gray, 2007; Perkins-Ceccato, Passmore, & Lee, 2003). Therefore, we similarly propose that some older adults may lack the motor capacity required to use 'automatic' processes effectively to regulate posture, and thus must shift to relying on conscious processes. In contrast, older adults with higher levels of skill will be better able to effectively perform balance tasks using 'automatic', lower-level processes, which are then disrupted through conscious processing.

There is preliminary support for such perspective. For instance, Manor et al. (2010) found that older adults with balance and somatosensory impairments showed the greatest disruptions in balance when their opportunity for conscious processing was restricted (through a distracting secondary task). These results fit the idea that age-related decline in balance and somatosensory function increases reliance on conscious processing to support postural control (see Clark, 2015). More direct evidence comes from Kal et al. (2019) who conducted a randomised trial to compare the effects of instructions that either promote (internal focus) or discourage (external focus; Kal et al., 2013; Wulf & McNevin, 2001) CMP during stroke rehabilitation. Participants' balance capacity, measured with the Berg Balance Scale (BBS), influenced the relative effectiveness of these interventions; internal focus instructions led to greater improvements in balance performance for individuals with relatively low capacity, while external focus were most effective for individuals with relatively high capacity (see Kal et al., 2015, for similar results in a stepping task after stroke).

Combined, there is some preliminary support for the notion that older adults' balance capacity modifies the influence of conscious processing on postural control. Yet this evidence is mostly indirect, based on patient populations (Kal et al., 2015; Kal et al., 2019), or on studies that did not directly manipulate or measure CMP (Manor et al., 2010). Therefore, the aim of this study was to address these issues. This will improve our understanding of the mechanisms governing postural control in healthy aging, and inform clinical decision making regarding the use of interventions that either promote or discourage conscious processing of balance.

The present study directly tested the hypothesis that balance capacity modifies the effects of CMP on postural control in older adults. Postural control was evaluated in three ways. First, we assessed performance itself by calculating postural sway amplitude, with lower values indicating better performance. Second, we assessed outcomes associated with movement automaticity by calculating both the frequency (mean power frequency) and complexity (sample entropy) of sway. For both measures, lower values have been reported to indicate conscious control of posture, whereas higher values point toward greater reliance on automatic control processes (e.g., Rhea, Diekfuss, Fairbrother, & Raisbeck, 2019; Richer & Lajoie, 2020; Roerdink, Hlavackova, & Vuillerme, 2011; Wulf & McNevin, 2001). Third, we assessed older adults' use of sensory feedback to control balance, and particularly their reliance on open- and closed-loop control, by means of a stabilogram diffusion analysis (SDA; Collins & De Luca, 1993; Collins, De Luca, Burrows, & Lipsitz, 1995).

For the group as a whole (regardless of balance capacity), we hypothesised that promoting CMP (by means of instructions, see methods) would result in (1) greater sway amplitude (i.e., reduced performance), (2) lower sway frequency and complexity (i.e., reduced automaticity; e.g., Roerdink et al., 2011), and (3) a greater predominance of closed-loop feedback mechanisms (Ellmers, Kal and Young, 2021)Ellmers, Kal, & Young, 2021; Wuehr et al., 2013 i.e., reduced critical time and reduced short-term diffusion; see methods for details on these outcomes).

However, we predicted that balance capacity would influence these results. Specifically, we predicted that increased CMP would be most detrimental (i.e., decreased balance performance) for those with higher balance capacity, and most beneficial for those with worse balance capacity. We used the above-described automaticity and SDA outcomes to explore the underlying postural control changes through which balance capacity modifies the impact of conscious processing on balance performance. No specific hypotheses were formulated with regards to how balance capacity may influence these outcomes, due to a lack of experimental data to inform these.

2. Methods

2.1. Participants

Fifty healthy, community-dwelling older adults were recruited from local social groups and exercise classes. Participants were eligible for inclusion if they were (i) ≥60 years of age, (ii) community-dwelling, (iii) without major cognitive impairment (Montreal Cognitive Assessment; Nasreddine et al., 2005), as evidenced by MoCA>18 (Dupré et al., 2020; Freitas, Simões, Alves, & Santana, 2013), and (iv) did not have neurological or musculoskeletal disorders/injuries that prevented them from walking 10 m without a walking aid. These criteria enabled us to include a representative group of older adults with a range of balance capacity scores. Institutional ethical approval was obtained from the local ethics committee. All participants provided written informed consent prior to participation.

A power analysis (G*Power, v3.1.9.2) showed that for a repeated measures ANOVA analyses a minimum of 46 participants would be required to be able to detect a significant within-between interaction of medium effect size ($f = 0.25$; assuming 1-$\beta = 90\%$, $\alpha = 0.05$, $r = 0.5$, 2 groups, and 2 within-subject conditions).[1]

2.2. Background characteristics

The assessment of background characteristics and the force plate assessments (see section 2.3) were conducted on the same day. First, participants' general cognition was screened using the MoCA (score range: 0–30), while the Trail Making Test-B (TMT—B; time-to-complete in seconds; Tombaugh, 2004) was used to assess working memory. Motor assessments included dominant hand grip strength (kgf), Berg Balance Scale (BBS; general balance; scale range: 0–56; Berg, Wood-Dauphinee, Williams, & Maki, 1992), and Timed-Up-and-Go (TUG in seconds; mobility; Podsiadlo & Richardson, 1991). Dominant hand grip strength was assessed using a handheld dynamometer, with the dominant arm held in a 90° angle. The BBS is commonly used for clinical assessment of functional balance capacity (Avers & Wong, 2020). It takes approximately 10 min to administer and consists of 14 tasks (ranging from sit-to-stand to balancing on one foot). Each item is scored 0–4, with higher scores reflecting greater independence (and, hence, 56 is the maximal score). TUG is a widely used clinical test of functional mobility and gait. Participants are required to stand up from a chair, walk 3 m, then turn around and walk back to the chair, and sit down again. Shorter completion times indicate better performance. All participants also completed the 10-item Movement Specific Reinvestment Scale (MSRS; scale range: 10–60) to determine their trait preference to consciously process their movements (Masters, Eves, & Maxwell, 2005). Finally, the Falls Efficacy Scale-International (Yardley et al., 2005) was used to assess participants' concerns about falling. Please see Table 1 for participant demographic information.

2.3. Procedure

All participants completed 60-s, narrow-stance (feet 10 cm apart) balance trials on an AccuSway force platform (500 × 500 mm; AMTI Inc., Watertown, MA, USA). Position of the feet was marked to ensure consistency between trials. Participants stood with their hands by their sides looking straight ahead at a cross affixed to a wall 3 m away. They were instructed to stand quietly and maintain their balance (similar as in Zaback, Luu, Adkin, & Carpenter, 2021). Participants completed a single 60-s trial of the task under two different conditions in a counterbalanced order: high- and low-conscious movement processing (high- vs. low-CMP). Previous work has shown that one 60-s trial (when sampling at ≥100 Hz) is sufficient to obtain stable force plate estimates (Van der Kooij, Campbell, & Carpenter, 2011). In the high-CMP condition, participants were informed that they would hear a beep at a certain point during the trial. Upon hearing this beep, their task was to (1) tell the experimenter where their weight was currently distributed beneath their feet (e.g., more forwards/backwards (toes/heels) or left-right), and (2) how the weight distribution had changed in the 10 s prior to the beep. Although participants were told that the beep could occur at any point during the trial (after the initial 10 s had passed), in fact the beep always occurred at the end of the trial, once data had stopped recording.[2] As participants completed one 60-s trial for each experimental condition, we reasoned that they would not realise the deception and anticipate the timing of the beep. For the low-CMP condition, participants completed a continuous secondary task while balancing that aimed to distract attention away from balance and thus limit the opportunity for CMP. The task required participants to continuously verbalise the months of the year (in the correct order), starting with January, for the duration of the 60-s trial. This task was chosen as it should substantially restrict participants' opportunity to consciously process movement – but at the same time presents relatively low cognitive demands.

2.4. Data analysis

2.4.1. Force plate data

All analysis of force plate data were performed with custom-made/adapted MATLAB scripts (R2019b; MathWorks, Natick, MA; see our Open Science Frame repository for access to these analysis scripts: https://osf.io/bwjmk). Moments and ground reaction forces were sampled at 500 Hz and subsequently low-pass filtered offline with a bidirectional, second order Butterworth filter (cut-off frequency: 5 Hz), before estimating the centre-of-pressure coordinates. We then assessed the amplitude, frequency, and complexity of anterior-posterior and mediolateral postural adjustments by calculating the root-mean-square (RMS, mm), mean power frequency (MPF; mean frequency in power spectrum after fast Fourier transformation), and sample entropy (SEn; Lake, Richman, Griffin, & Moorman, 2002; Roerdink et al., 2011) of COP data. Sway amplitude (RMS) served as the main balance performance variable. MPF and SEn were secondary outcomes. Lower MPF represents more low-frequent postural adjustments, which are thought to reflect increased

[1] We chose to use a repeated measures ANOVA analysis to base our power analysis on, as we are not aware of software packages that allow us to directly do power analysis for the generalised estimating equation analysis (GEE-analysis) we used in this study. We argue this to be most closely aligned with the type of analysis we performed– i.e., looking at the main (within-subjects) effect of conscious processing condition and its interaction with balance capacity (between-subjects factor). Note that in our regression analysis balance capacity was a continuous variable rather than a group variable (as which it is defined here for the sake of the power analysis).

[2] Participants were informed that they would have to repeat the trial if they provided any incorrect answer to either question. This deception was deemed necessary to ensure appropriate adoption of the experimental manipulation. However, participants' responses were not checked for accuracy and trials were not repeated. Participants were debriefed about this deception afterwards.

Table 1
Patient characteristics.

	Older Adults ($N = 47$)		
	n	Mean ± SD	Range
General characteristics			
Age in years		74.8 ± 7.1	61–88
Sex (male/female)	13/34		
Height (cm)		164.4 ± 9.9	136–192
Weight (kg)		70.3 ± 15.8	37–116
BMI		25.9 ± 4.1	17.5–37.9
No. daily medications		2.9 ± 2.2	0–10
Motor function			
BBS (0–56)		52.4 ± 3.2	42–56
TUG (s)		11.2 ± 3.3	7.0–22.6
BBS/TUG (balance capacity composite score)		5.0 ± 1.4	1.9–8.0
Handgrip strength (kg)		23.6 ± 9.0	10.9–49.4
# falls in last 12 months (0/1/2/3)	32/10/2/3		
Cognitive function			
MoCA (0−30)		26.4 ± 2.9	20–30
TMT-B (s)		98.3 ± 51.1	31.2–248.5
MSRS (10–60)		23.6 ± 11.8	10–57
FES-I (16–64)		22.5 ± 5.1	16–40

NB: BMI = Body Mass Index; BBS = Berg Balance Scale; TUG = Timed-up-and-Go; MoCA = Montreal Cognitive Assessment; n = number; TMT-B = Trail Making Test, part B; MSRS = Movement-Specific Reinvestment Scale; FES-I = Falls Efficacy Scale–International;

CMP (Ellmers et al., 2021; Richer & Lajoie, 2020; Wulf et al., 2001). SEn is a measurement of movement complexity. Lower values reflect more regular, less complex postural control, and purportedly greater CMP (Rhea et al., 2019; Richer & Lajoie, 2020; Roerdink et al., 2011). As recommended (Lake et al., 2002), we optimised the parameter settings required for the SEn calculation, resulting in the use of $m = 3$ and $r = 0.01$.

Finally, we performed a stabilogram diffusion analysis (SDA; Collins & De Luca, 1993; Collins et al., 1995) to investigate how CMP might impact on participants' reliance on closed- and open-loop postural control, and how this might be different for people with lower or higher balance, respectively. During quiet standing tasks, the velocity of an individual's centre-of-pressure displays persistent behaviour at short time intervals, when open-loop control predominates. Anti-persistent behaviour is evident at longer time intervals, as closed-loop control mechanisms come into play when centre-of-pressure velocity reaches a specific threshold (Delignières, Torre, & Bernard, 2011). We determined the critical time (s) and displacement (mm^2) at which corrective feedback mechanisms begin to predominate, with lower values indicating greater influence of closed-loop processes. We further calculated the short-term diffusion coefficient (D_s; mm^2/s). Higher values indicate greater short-term stochastic activity, which has been linked to less-tightly regulated control of posture (e.g., Collins et al., 1995; Wuehr, Brandt, & Schniepp, 2017).

To ensure that our SEn and SDA outcomes were comparable to previous research, and to avoid issues of oversampling (Rhea et al., 2011), force plate data were down sampled to 100 Hz prior to both analyses.

2.4.2. *Manipulation check*

After each trial, participants completed the 2-item "conscious motor processing" subscale of the shortened state version of the MSRS (Ellmers & Young, 2018). Scores range between 2 and 12, with higher scores indicating greater conscious processing of movement. This scale was used to confirm whether the conscious processing manipulation had the intended effect.

2.4.3. *Balance capacity*

To obtain a comprehensive measure that incorporates multiple aspects of balance capacity, we decided to calculate a composite score based on the BBS and TUG assessments. This was achieved by dividing BBS score by TUG score, with higher scores thus reflecting better functional balance capacity. In this way, we aimed to include both general balance and mobility, while also circumventing possible ceiling effects associated with BBS (Pardasaney et al., 2012).

2.5. *Statistical analysis*

All statistical analysis were performed with SPSS (version 26; IBM, NY, USA). We first assessed whether experimental manipulations were successful, using a separate Wilcoxon signed rank tests to compare state-CMP scores between high-CMP and low-CMP.

Generalised estimating equations (GEE) were used to compare the effects of CMP condition on balance performance (sway amplitude, RMS), automaticity (frequency, MPF; complexity, SEn), and reliance on open- vs. closed-loop control (critical time and displacement, and D_s). GEE is a regression analysis that accounts for correlation between repeated measurements. In this sense it is an alternative to repeated measures ANOVA, albeit more flexible, as it does not assume data to be normally distributed. An exchangeable working correlation matrix defined dependency amongst measurements.

Next, we determined whether effects of CMP condition on these outcomes were influenced by participants' balance capacity (composite BBS-TUG score), by adding this variable to the GEE-models (similar analysis approach as in Kal et al., 2015; Kal et al., 2019). This would be evidenced by a significant BBS-TUG by CMP condition interaction. For all analyses alpha was set at 0.05. Effect sizes were reported as $r = (\frac{z}{\sqrt{N}})$ (Field, 2009).[3]

Underlying data and Matlab scripts used can be accessed on the Open Science Framework (https://osf.io/bwjmk).

3. Results

3.1. Participant characteristics

In total, data were collected for 50 older adults. However, due to a technical issue, force plate data was not recorded correctly for 3 participants. These participants were therefore removed from all further analyses. The characteristics of the remaining 47 participants, including their balance capacity scores, can be found in Table 1.

On average, participants were mid-seventies and had slightly worse balance than the norms for BBS (54 for men, 53 for women) and TUG scores (9 s for both men and women) for this age group (Steffen, Hacker, & Mollinger, 2002). Scores varied considerably, however, with some scoring as low as 42 on the BBS and/or taking >20 s to complete the TUG (both >3–4 SDs below the norms). For the balance capacity composite measure, which served as input for the analysis presented below, no such normative data are available, but they directly relate to these outcomes. We present a graphical distribution of these scores in Fig. S1 on OSF (https://osf.io/bwjmk).

3.2. Manipulation checks

State-CMP was significantly higher in the high-CMP ($Mdn = 11$, $IQR = 2$) compared to low-CMP condition ($Mdn = 7$, $IQR = 6$; $Z = 5.304$, $p < .001$, $r = 0.774$).

3.3. Balance performance

3.3.1. Sway amplitude (RMS)

Panels A-B of Fig. 1 summarise the main results. The CMP manipulation had no significant effect on either mediolateral (Wald $\chi^2(1) = 0.382$, $\beta = 0.158$, $p = .537$, 95% CI = [−0.342, 0.658]) or anterior-posterior sway amplitude (Wald $\chi^2(1) = 0.522$, $\beta = -0.211$, $p = .470$, 95% CI = [−0.785, 0.362]).

Balance capacity significantly influenced the effect of CMP-manipulation on mediolateral sway (Wald $\chi^2(1) = 5.167$, $\beta = 0.333$, $p = .023$, 95% CI = [0.046, 0.620]). This interaction effect was due to balance capacity being positively associated with sway amplitude in the high-CMP condition ($\beta = 0.273$), but not in the low-CMP condition ($\beta = -0.060$). This finding implies that older adults with higher balance capacity demonstrate greater increases in postural sway when asked to consciously process their balance. In contrast, balance capacity did not affect sway amplitude during conditions where older adults are distracted from consciously processing their balance. Balance capacity did not influence the effects of CMP on anterior-posterior sway (Wald $\chi^2(1) = 0.056$, $\beta = 0.040$, $p = .812$, 95% CI = [−0.288, 0.367]).

3.3.2. Automaticity measures: Sway frequency (MPF) and complexity (SEn)

Significant effects of the CMP manipulation were found for sway frequency in the mediolateral (Wald $\chi^2(1) = 7.497$, $\beta = -0.051$, $p = .006$, 95% CI = [−0.088, −0.015]) and anterior-posterior direction (Wald $\chi^2(1) = 12.225$, $\beta = -0.070$, $p < .001$, 95% CI = [−0.109, −0.031]). Sway frequency was significantly lower in both directions in the high-CMP condition compared to the low-CMP condition (Fig. 1, panels C-D; ΔMPF-ML = 0.051 Hz, $r = 0.400$; ΔMPF-AP = 0.070 Hz, $r = 0.510$).

Regarding movement complexity, mediolateral SEn was significantly impacted by the CMP manipulation (Wald $\chi^2(1) = 5.556$, $\beta = -0.046$, $p = .018$, 95% CI = [−0.084, −0.008]), with significantly lower complexity noted during the high-CMP condition (Δmediolateral SEn = 0.046, $r = 0.349$). In contrast, anterior-posterior SEn was not significantly different between the different CMP conditions (Wald $\chi^2(1) = 2.519$, $\beta = -0.033$, $p = .112$, 95% CI = [−0.073, 0.008]) – see panels *E*-F of Fig. 1.

Further analyses revealed that balance capacity influenced the effects of the CMP manipulation on both mediolateral sway frequency (Wald $\chi^2(1) = 6.639$, $\beta = -0.031$, $p = .010$, 95% CI = [−0.055, −0.007]) and mediolateral sway complexity (Wald $\chi^2(1) = 10.499$, $\beta = -0.042$, $p = .001$, 95% CI = [−0.067, −0.017]). This interaction effect was explained by balance capacity being negatively associated with movement frequency ($\beta = -0.013$) and complexity ($\beta = -0.019$) during high-CMP, while being positively associated with frequency and complexity in low-CMP (MPF: $\beta = 0.019$, SEn: $\beta = 0.023$). Thus, older adults with higher balance capacity showed stronger *reductions* in mediolateral sway frequency and complexity when they consciously processed their balance, but stronger

[3] We had originally planned to conduct a secondary analysis to test how effects of the CMP manipulation on postural control would potentially be influenced by older adults' working memory (as assessed using the TMT-B scores), and trait-conscious movement processing (as assessed using the conscious movement processing subscale of the Movement-Specific Reinvestment Scale). Based on feedback on an earlier draft, we decided against including these analyses and results in the current paper. For the sake of transparency, these can be accessed, along with the rest of the data and analyses, on the Open Science Framework: https://osf.io/bwjmk. Neither factor was found to significantly influence the effects of CMP on any of the outcomes. This also suggests that our decision to recruit older adults with a relatively wide range of cognitive functioning scores did not impact on our findings.

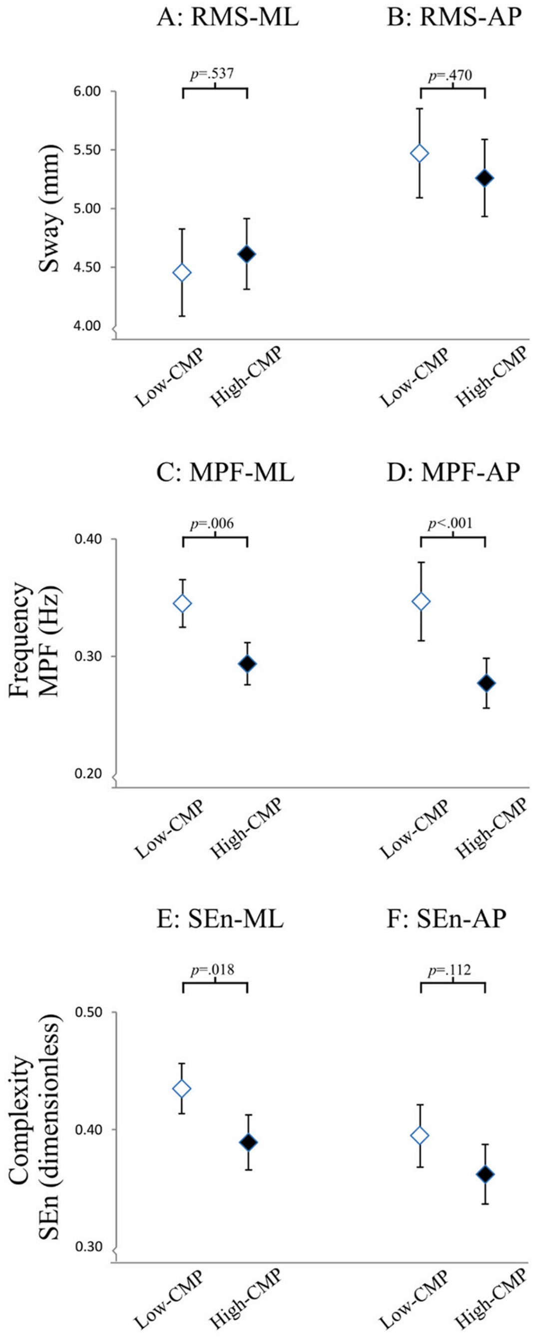

Fig. 1. Mean sway amplitude (RMS in mm, panels A-B), mean power frequency (Hz, panels C—D), and sample entropy (SEn, panels *E*-F) variables in both the mediolateral (ML) and anterior-posterior (AP) planes of movement. Data are presented separately for low-CMP and high-CMP conditions. Error bars represent standard errors.j

increases in frequency and complexity when they were distracted from consciously processing balance. Balance capacity did not influence the effects of CMP on anterior-posterior sway frequency (Wald $\chi^2(1) = 0.261$, $\beta = 0.006$, $p = .610$, 95% CI = [−0.016, 0.027]) or anterior-posterior sway complexity (Wald $\chi^2(1) = 0.948$, $\beta = -0.015$, $p = .330$, 95% CI = [−0.044, 0.015]).

3.3.3. *Reliance on open- vs. closed-loop control: SDA outcomes*

SDA results are presented in Fig. 2. While critical time period seemed somewhat higher in the high-CMP condition (panels A-B), no significant effects of the CMP manipulation were found for either the mediolateral (Wald $\chi^2(1) = 3.061$, $\beta = 0.140$, $p = .080$, 95% CI = [−0.017, 0.297]) or anterior-posterior direction (Wald $\chi^2(1) = 1.399$, $\beta = -0.090$, $p = .237$, 95% CI = [−0.059, 0.239]).

Similarly, no significant changes were observed in critical values in either the mediolateral (Wald $\chi^2(1) = 0.398$, $\beta = -7.644$, $p = .528$, 95% CI = [−31.394, 16.107]) or anterior-posterior direction (Wald $\chi^2(1) = 0.978$, $\beta = -10.616$, $p = .323$, 95% CI = [−31.656, 10.425]), see Fig. 2, panels C—D.

D_s values were found to be significantly affected by the CMP manipulation in the anterior-posterior direction (Wald $\chi^2(1) = 7.967$, $\beta = -10.694$, $p = .005$, 95% CI = [−18.120, −3.268]), with significantly higher short-term diffusion coefficients observed during the high-CMP condition (Δanterior-posterior $D_s = 10.694$, $r = 0.500$, see panel F of Fig. 2). No significant difference was found for the mediolateral D_s (Wald $\chi^2(1) = 2.018$, $\beta = -4.528$, $p = .155$, 95% CI = [−10.776, 1.720]).

Further analysis revealed no significant interactions between balance capacity and any of the abovementioned SDA outcomes (Wald χ^{2}'s(1) ≤ 1.261, p's ≥ 0.261).

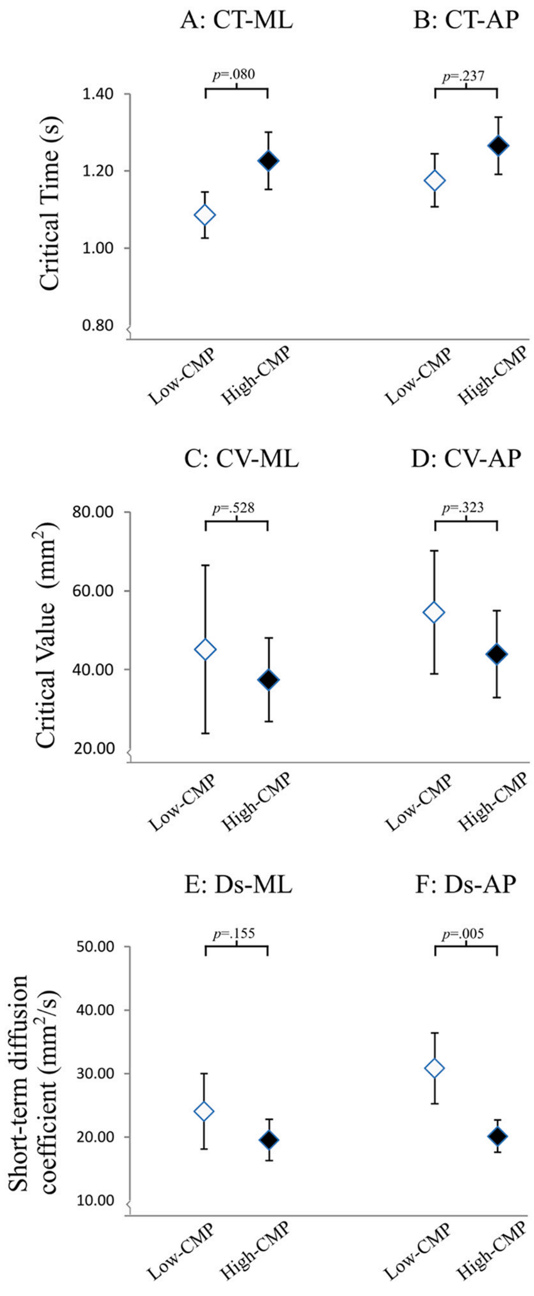

Fig. 2. Mean critical time period (CT in seconds, panels A-B), critical values (CV in mm^2, panels C—D), and short-term diffusion coefficients (Ds, in mm^2/s; panels E-F). Data are presented separately for the mediolateral (ML) and anterior-posterior (AP) planes of movement, and for low-CMP and high-CMP conditions. Error bars represent standard errors.

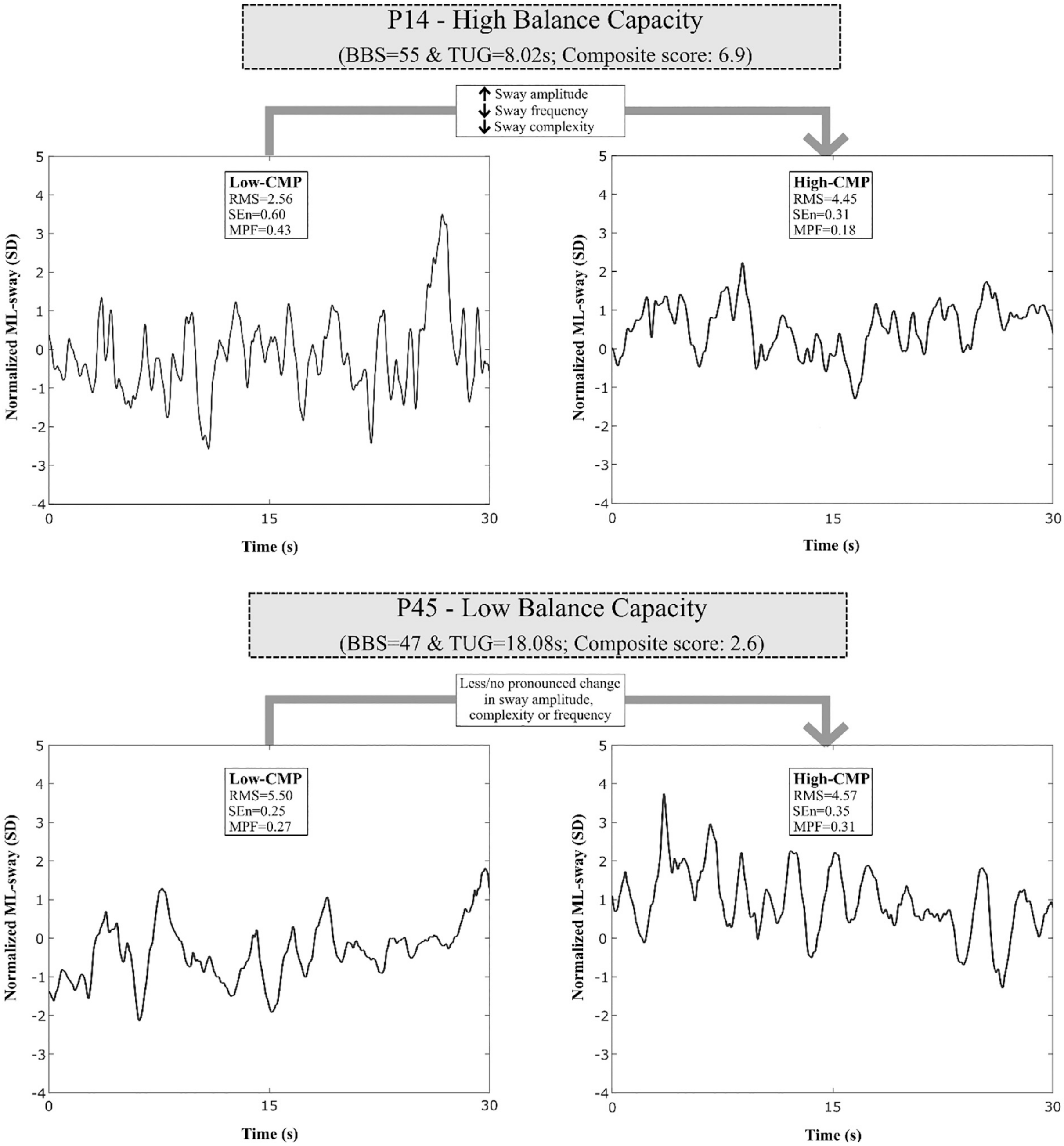

Fig. 3. Examples of normalised mediolateral (ML) sway patterns for one older adult with high balance capacity (P14, upper panels) and one with relatively low balance capacity (P45, bottom panels). The differences in raw sway amplitude between participants and conditions would make it difficult to visually compare the shape of the sway patterns. Therefore, to enhance visual inspection, we show the first 30 s of each trial. For the same reason, normalised sway is presented (i.e., by dividing it by its standard deviation; as in Roerdink et al., 2011). We only showed ML sway as effects were largely restricted to this plane of movement, likely due to the narrow stance position predominantly challenging stability in that direction (Sullivan, Rose, Rohlfing, & Pfefferbaum, 2009). Mean overall sway amplitude (RMS), complexity (SEn), and frequency (MPF) for the whole 60s trial are displayed in the text box in each panel. As can be seen, P14 switched to a less complex (more predictable/regular), low frequency sway pattern in the high CMP condition (upper right panel) compared to the low CMP condition (upper left panel). For P45, the participant with relatively low balance capacity, differences between conditions in terms of complexity and frequency were less pronounced.

3.4. Summary of results on modifying influence of balance capacity

Overall, balance capacity modified the influence of conscious processing on mediolateral sway amplitude, frequency, and complexity, but no effects were evident with regards to the reliance on open- vs. closed-loop control processes. Fig. 3 illustrates these combined findings by plotting mediolateral sway in the two experimental conditions for a participant with low (P45) and high balance capacity (P14). As can be observed, individuals with higher balance capacity made less complex and less frequent mediolateral postural adjustments during high-CMP (indicating lower automaticity), but more complex and more frequent adjustments during low-CMP (indicating greater automaticity).

4. Discussion

We investigated whether balance capacity modified the effects of CMP on postural control in older adults. Participants' balance capacity was found to significantly influence the effects of CMP with respect to amplitude, frequency, and complexity of mediolateral postural sway. Specifically, during high-CMP, having better balance capacity was associated with greater *increases* in postural sway amplitude, and greater *reductions* in sway frequency and complexity. Balance capacity did not influence the effects of conscious processing on older adults' relative reliance on open- vs. closed-loop postural control.

Older adults with higher balance capacity were more likely to show increased mediolateral sway (i.e., reduced balance performance) in the high-CMP condition. This is in line with our predictions, and with earlier findings on motor performance in both sporting contexts (e.g., Beilock et al., 2002; Castaneda & Gray, 2007) and people after stroke (Kal et al., 2015; Kal et al., 2019). Combined, these findings indicate that performers with higher levels of skill may be particularly vulnerable to the disruptive influence of CMP. We suggest that this result is due to these individuals being able to effectively perform the given task using 'automatic', lower-level processes, which are then disrupted through conscious input.

Further analysis showed that balance capacity also shaped the effects of conscious processing on both sway frequency and complexity. During high-CMP, higher balance capacity was associated with less frequent and less complex mediolateral postural sway – indicating a more pronounced shift to conscious processing of balance, i.e., reduced automaticity (Roerdink et al., 2011; Wulf & McNevin, 2001). The reverse was also true during low-CMP, with higher balance capacity associated with greater shifts toward automaticity (*more* frequent and complex mediolateral postural sway). These findings suggest that higher balance capacity allows older adults to flexibly adapt to task demands, more readily shifting between automatic and conscious modes of control as required. While this shift to a more conscious mode of postural control appeared to negatively impact balance performance (increased sway amplitude) during the present research, we suggest that the ability to flexibly use conscious control will be beneficial during complex tasks for which automatic control is insufficient to ensure successful performance (i.e., walking on slippery surface, or negotiating obstacles). In contrast, those with lower balance capacity appear to exhibit a more constrained mode of postural control throughout, irrespective of experimental manipulation. These results cannot simply be explained by balance capacity influencing the degree to which people adhere to the experimental manipulations; additional GEE-analysis showed that the high CMP condition elicited similar changes in self-reported state-CMP, regardless of balance capacity ($p = .517$).

Regarding the main effects of the conscious processing manipulation, as hypothesised, we observed overall reduced sway frequency and complexity during the high-CMP condition. This fits with earlier work (e.g., Polskaia et al., 2015; Potvin-Desrochers, Richer, & Lajoie, 2017; Richer, Polskaia, & Lajoie, 2017), and indicates a less automatic motor control strategy. In contrast to these previous studies, though, in the current study overall reduced balance automaticity was not accompanied by overall reduced balance performance (i.e., increased sway). As discussed in the previous paragraph, this discrepancy is likely due to our sample consisting of people with varying levels of balance skill, ranging from high- to comparatively low-functioning older adults (see Table 1). Indeed, the higher-functioning older adults seem to have been negatively affected much the same as in these previous studies, whereas lower-functioning older adults were not. Changes in sway amplitude, frequency, and complexity were most pronounced in the mediolateral plane, which seems due to balance being most challenged in this direction in the narrow stance task (see also Raffegeau et al., 2020).

Contrary to our hypothesis, the CMP manipulation did not overall significantly change the relative contributions of open- vs. closed loop processes to postural control. We did observe the hypothesised significant reduction in short-term diffusion in the high-CMP condition, suggesting more tightly regulated postural control (Collins et al., 1995). However, this finding needs to be interpreted cautiously, as it was only evident in the anterior-posterior condition, and this result was only based on a single trial, while 5 trials per condition may be required to obtain more reliable SDA estimates (Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2007).

A potential limitation of our study concerns the experimental manipulation used to induce CMP. Participants were aware that they would need to describe their sway. They therefore may have purposely adopted a strategy that allowed them to better perceive and report on their sway. We cannot definitively rule out this option. However, if true, we would have likely expected that the SDA analysis would have revealed a strong shift toward greater involvement of closed-loop (i.e., sensory feedback) control processes during the high-CMP condition. As no significant changes in critical time nor critical value were evident, this does not seem to support this alternative interpretation (although as noted earlier the power of this analysis might have been limited due to the use of one trial only; Doyle et al., 2007). Further, participants reported a similar substantial increase in self-reported conscious processing in response to the high-CMP manipulation, regardless of their balance capacity. Hence, even if true, this alternative explanation would not change our main conclusion that (i) conditions of high CMP negatively affected older adults with relatively good, but not low, balance capacity, and (ii) older adults with relatively good balance capacity were better able to shift between conscious and automatic modes of balance control.

A second potential limitation relates to the verbalisation involved in the low-CMP condition. However, other studies that used nonverbalised distracting cognitive tasks to limit conscious processing of balance obtained very similar patterns of results as in our study: i.e., increased sway frequency and complexity when distracted vs. during non-distracted performance (Richer et al., 2017; Richer & Lajoie, 2020; Stins, Michielsen, Roerdink, & Beek, 2009). Note also that participants reported a very significant reduction in state conscious processing (see manipulation checks). As such, we are confident that our experimental manipulation worked as intended, and that the effects found in our study were due to changes in conscious processing, while verbalisation likely played a trivial role.

The current study demonstrates the importance of considering (and controlling for) functional balance capacity when comparing the effects of attentional focus on balance performance in older adult populations. Further, identification of factors that mediate responses to attentional manipulations (e.g., age-related changes in musculoskeletal physiology) will be critical for optimising treatment. They also challenge the ubiquitous – yet seemingly confounded – opinion that diverting attention away from movement performance itself (e.g., using secondary tasks or external focus instructions) will always benefit motor control, regardless of underlying pathology. The need for such progression is exemplified by recent findings in the context of neurorehabilitation, where stroke patients experienced difficulty performing a balance skill while adopting an external focus of attention – difficulties that only gradually and partially subsided after extended practice (Kal et al., 2019).

In conclusion, our results show that balance capacity influences the effects of CMP on postural sway in older adults. Older adults with higher balance capacity seem better able to readily shift between more conscious and more automatic modes of control. This could potentially make them more resourceful when dealing with varying task demands in daily life – for example, during tasks of high difficulty in which automatic control processes alone may not guarantee successful performance. Future studies are needed to replicate these findings across balance tasks of different complexity, and different clinical populations.

Author note

The authors declare that they have no competing interests.

CRediT authorship contribution statement

Elmar C. Kal: Conceptualization, Methodology, Data curation, Software, Writing – original draft. **William R. Young:** Conceptualization, Methodology, Writing – review & editing. **Toby J. Ellmers:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2022.102933.

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