How providing more or less time to solve a cognitive task interferes with upright stance control; a posturographic analysis on healthy young adults

Patrice R Rougier
Laboratoire de Physiologie de l'Exercice, EA4338, Université de Savoie, Domaine Scientifique de Savoie-Technolac, 73376 Le Bourget du Lac cedex, France.

Cédrick T Bonnet
Univ. Lille, CNRS, UMR 9193 – SCALab – Sciences Cognitives et Sciences Affectives, F-59000 Lille, France

Corresponding author: P R Rougier
tel: (33) 4 79 75 81 46
fax: (33) 4 79 75 81 48
e-mail: patrice.rougier@univ-savoie.fr

Conflict of interest: none

Abstract
Contrasted postural effects have been reported in dual-task protocols associating balance control and cognitive task that could be explained by the specificity of the cognitive task and the biomechanical significance of the force platform data. To better assess these effects, eleven healthy young adults were required to stand upright quietly on a force platform while concomitantly solving mental-calculation or mental-navigation cognitive tasks. Various levels of difficulty were applied by adjusting the velocity rate, or delay, at which the instructions were provided to the subject according to his/her maximal capacities measured beforehand. A condition without any concomitant cognitive task was added to constitute a baseline behavior. Two basic components, the horizontal center-of-gravity movements and the horizontal difference between center-of-gravity and center-of-pressures were computed from the complex center-of-pressure recorded movements. It was hypothesized that increasing the delay should infer less interaction between postural control and task solution. The results indicate that both mental-calculation and mental-navigation tasks induce reduced amplitudes for the center-of-pressure minus center-of-gravity movements, only along the mediolateral axis, whereas center-of-gravity movements were not affected, suggesting that different circuits are involved in the central nervous system to control these two movements. Moreover, increasing the delays task does not infer any effect for both movements. Since center-of-pressure minus center-of-gravity expresses the horizontal acceleration communicated to the center-of-gravity, one may assume that the control of the latter should be facilitated, inferring reduced center-of-gravity movements, which is not seen in our results. This lack of effect should be thus interpreted as a less efficient control of these center-of-gravity movements. Taken together, these results suggest a detrimental role played by mental tasks requiring attention on undisturbed upright stance control, whatever their nature (calculation or navigation) and their relative difficulty. These data highlight the role played by instructions, i.e. focusing on our body movements or on the opposite diverting the attention, in the evaluation of upright stance control capacities and confirm the complex relation between center-of-gravity and center-of-pressure movements.

Keywords: attention, postural control, center-of-pressure, center-of-gravity, task difficulty

1.**Introduction**

Postural control is a complex sensorimotor task requiring the participation of various structures of the central nervous system including the spinal cord, the brain stem, the cerebellum, and the cortex (Maki & Mc Ilroy, 2007). Even though standing can be easily and automatically achieved without particular attention (one can, for instance, stand for long periods and speak in parallel), one can also be required to focus on his/her balance as a task when participating in a scientific experiment.

The effects of change in attention on postural control have been investigated for three decades using dual-task protocols. Compared to a single task, in which subjects are required to only focus on their postural stability, performing a cognitive task has noticeable effects on postural stability since decreased or increased postural movements have been reported (see Woollacott & Shumway-Cook, 2002 and Lacour Bernard-Demanze, & Dumitrescu, 2008 for review). Several factors, relative to the specificity of the task and the way postural control is analyzed, are thought to be responsible for these contrasted results. If various studies documented the effect of the nature and difficulty of the cognitive task (Fraizer & Mitra, 2008; Hwang, Lee, Chang, & Park, 2013; Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Pellechia, 2003; Riley, Baker, & Schmit, 2003), only a few studies aimed to question the way postural control was analyzed, and notably the mechanisms underlying the CP displacements. The CP is a complex variable since it comprises both the vertically projected displacements of CG_v and its difference ($CP\text{-}CG_v$). Both variables do not have the same meaning as CG_v is often used to assess the postural performance and therefore the efficiency of postural control whilst $CP\text{-}CG_v$ a fair index of the neuro-muscular means called into play for achieving the postural control. This last point can be easily emphasized by using forwardly leaning postures which solicit in larger proportion the calf muscles (Rougier, Burdet, Farenc, & Berger, 2001). In that case, only the amplitudes of the $CP\text{-}CG_v$ movements increase whereas those of the CG_v remain unchanged. In addition, by being proportional to the horizontal acceleration communicated to the CG (Brenière, Do, & Bouisset, 1987), the $CP\text{-}CG_v$ amplitudes make more or less complex the CG control. As a result, a decrease of the $CP\text{-}CG_v$ movements should be viewed as facilitating the control of the CG_v and therefore of the whole posture whereas its increase should worsen the CG_v control. Using this partitioning, Vuillerme and Nafati (2007) have highlighted that focusing on postural control impacted more the $CP\text{-}CG_v$ movements than the CG_v movements, thus confirming the EMG decrease in dual-tasks observed in older peoples by Simoneau, Billot, Martin, Perennou & van Hoecke (2008). Later, the same authors (Nafati & Vuillerme, 2011) reported concomitant decreases of $CP\text{-}CG_v$ and CG_v movements during a short-term digit-span memory task. Thus, whereas a $CP\text{-}CG_v$ decrease might be a characteristic feature of double tasks protocols, the contrasted results with CG_v movementsremain not fully understood. In our mind, we may better understand these contrasted results from a motor control point of view. Indeed, more or less CP displacements need not necessarily equate to more or less control. Differences in CP movements can be strategic, as has been discussed in the literature several times in the past decades. One way to differentiate the two explanations (less control vs. other kind of control) is to use the fractional Brownian motion (fBm) modelling (or stabilogram-diffusion analysis). In this modelling, the displacements (CP, CG_v or $CP\text{-}CG_v$) can be considered as the result of a combination of deterministic and stochastic (random walk) processes and the degree of correlation between past and future increments determines the nature of the processes. Interestingly, the computing of scaling regimes enables a quantification of these controls which, by analogy, may account for feedback (corrective) or feedforward (exploratory) control mechanisms (Collins and De Luca, 1993). We have also shown that the $CP\text{-}CG_v$ and CG_v movements were largely controlled over the shortest (exploratory) and longest times intervals (correction), respectively (Rougier & Caron, 2000). This two-parts strategy may reflect in fact two successive and alternative objectives for the postural control system to control standing still: exploratory (feedforward) movements over the short term (obtaining information about the postural system) and "performatory" (feedback) over the long term (using this information) (Riley, Wong, Mitra, & Turvey, 1997).

To improve our knowledge on the interference between attention and postural control, we used a dual-task protocol based on two cognitive tasks, mental-calculation (MC) or mental-navigation (MN), aimed at activating various cerebral areas directly or not related to postural control. The aim of this study was therefore twofold: 1) assessing whether mobilizing different brain structures could lead to differences in the

two elementary CP-CG_v and CG_v movements; 2) analyzing the form of the interaction between the cognitive tasks and postural control by modulating the time duration involved in solving the secondary cognitive tasks. Since the number of instructions constituting a cognitive task was held constant for all subjects or difficulties, inducing posturographic recordings of various durations, it was mandatory to retain parameters insensitive to trial durations to assess the postural control. Interestingly, the fBm modeling, by only focusing on time intervals and not time series (and therefore trial lengths) allows us to analyze and compare these recordings.

Our hypotheses were that 1) dual-tasks protocols should affect – here decrease – predominantly the neuro-muscular component of the CP movements, i.e. CP-CG_v movements, as shown by Vuillerme and Nafati (2007) and Nafati and Vuillerme (2011). As highlighted through visual feedback protocols, larger CP-CG_v movements are observed when attention is focused on stance control rather than on postural control with no visual feedback (Rougier, 2003). Diverting attention should therefore induce the reverse phenomenon, i.e. reduced CP-CG_v movements during dual-tasks conditions. A repercussion upon the CG_v component would depend on the capacity of the CNS to detect, treat and correct these CG_v movements, three actions which should be likely weakened in dual-tasks and which can be easily assessed through fBm modeling. In other terms, CG_v should be larger in dual-tasks even though CP-CG_v movements remain equal in amplitudes. 2) Providing more time to solve the cognitive task is expected to allow subjects to better control their balance, i.e. in our case to reduce CG_v movement. 3) As compared to the calculation task, the spatial navigation task, with a priori increased interferences at the brain level, should infer the larger postural effects, i.e. decreased CP-CG_v movements and possibly increased CG_v movements.

2. Methods

2.1. Subjects

Eleven healthy subjects (six males and five females, aged 21–26 years; weight: 70.2 ± 12.6 kg; height: 172 ± 9 cm; mean ± s.d.) with no known visual or balance pathology were included in this study. All subjects were students in sports and physical education and participated in sports regularly. The study was undertaken with the understanding and written consent of each subject, and its protocol was in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. The cognitive tasks

Two tasks were used in this study. The MC cognitive task consisted in mentally performing the addition of a sequence of integer numbers ranging between −9 and +9, 0 being excluded, starting at 0. These numbers were presented by the computer one after another. The MN cognitive task consisted in performing two-dimensional spatial displacements in a nine-cell square using four instructions (forward, backward, right, and left). The subjects had to achieve these tasks standing upright with their eyes closed. The subjects had to mentally imagine the displacements from a central position in the square. These two tasks involved performing as quickly as possible MC or MN exercises through successive instructions given step by step by the software associated with the force platform. To help the subjects stay focused on the task, the instructions were given through headphones that were covered by a soundproof helmet.

Before the postural measurements, pretests were performed for each subject to determine their maximal capacities (i.e., the shortest time for performing the task) in both MC and MN tasks. In these pretests, four trials of 20 successive instructions, during which the subjects had to press as quick as possible a keyboard button to get the next item, were used. These pretests were then used to set similar cognitive task difficulties during the test on the force platform. To this aim, the delay between the successive instructions, and therefore the difficulty of the cognitive tasks, was adjusted to the subject's own capacities. Nine conditions, each comprising five trials, were randomly proposed: one "single" task, used for assessing the baseline performance (ST), and 2*4 dual-tasks (DT_{100}, DT_{110}, DT_{120}, DT_{130}), corresponding to 100, 110, 120, and 130% of the maximal capacity (or minimal delay), respectively, for the MC and MN protocols. The higher the percentage, the longer the gap between successive instructions, and the longer the duration of the trials,

the easier the tasks are. As a result, the duration of the trials varied across subjects and conditions. For each subject, the duration of the ST trials was set to match the duration of the DT_{100} in the MN protocol. For all DTs, the final result, i.e., the final position with respect to the initial one (MN task) or the final number (MC task), was given by the subject. A correct answer was the condition for the trial to be included in the data analysis. Lastly, to avoid any initial effect on the results caused by an interference between the postural and cognitive tasks, the force platform data collection started, in all DT conditions, from the fifth instruction. Precise instructions were given to the subjects during the trials: for the ST condition, they were required to focus on their stability and therefore to stand as still as possible whereas for the DT conditions, their priority was to give at the end of the trail the correct answer to the cognitive task while standing still as much as possible.

The mean time intervals computed from the pretests were 0.516 s (± 0.088) and 1.095 s (± 0.184) for the MN and MC cognitive tasks, respectively. As a result, the mean trial durations for the sample were longer for a given capacity for the MC task than the MN task. Considering the objectives of the study, we preferred to put a slant on the cognitive task rather than on postural control in order to allow all subjects to achieve precisely the same task and therefore to challenge them with an identical level of difficulty. As a result, trial durations were quite variable from one subject to another, leading us to leave aside more traditional analyses such as surface with confidence intervals (Tagaki, Fujimara, & Suehiro, 1985) or the frequency approach classically used to assess the dynamic process of postural stabilization (Rougier, 2008). Our aim was also to make sure that the possible effects related to the cognitive task–postural control interaction could only affect one of the two components (CG_v, CP-CG_v) in our study. The inclusion in our protocol of DT_{100} conditions, the rejection of trials when the final response was erroneous, and the rhythm imposed by the software were methodological aspects ensuring that this purpose was achieved well. Lastly, it seemed important that the two cognitive tasks relied on working memory that may be viewed as an outcome of the ability to control attention and sustain its focus on a particular active mental representation in the face of distractive influence (Engle, Tuholski, & Kane**,** 1999).

2.3. Posturography

The subjects stood barefoot on a double force platform (Equi+, PF02, France) with the inner borders of the feet parallel, the heels 6 cm apart. They were asked, in all conditions, to keep their arms at their sides. The signals coming from the dynamometric load cells (range of measurements, 0–150 daN) were amplified and converted from analog to digital form through a 14-bit acquisition card and then recorded without any filtering on a personal computer with a 64-Hz frequency. The resultant center-of-pressure (CP) was then computed and decomposed along the mediolateral (ML) and anteroposterior (AP) axes. Rest periods of 50 s and of about 8 min were allowed between each trial and each condition, respectively, and automatically managed by the recording software.

2.4. Signal processing

CG_v and CP-CG_v movements were estimated from the CP displacements from a CG_v/CP ratio (Brenière, 1996; Caron, Faure & Brenière, 1997). The different steps of analysis to calculate CG_v and CP-CG_v movements are displayed in Fig. 1. This ratio, at a maximum level for the lower frequencies (CG_v and CP are characterized by similar positions at 0 Hz), tends toward zero above 3 Hz. The CG_v estimation consists in multiplying each amplitude of the CP spectra along both ML and AP axes, transformed in the frequency domain through a fast Fourier transform (FFT), by the CG_v/CP ratio and recovering to the time domain with an inverse FFT. Once estimated, CG_v and CP-CG_v displacements were analyzed through two methods.

The first method computed two parameters: 1) the mean body-weight distribution over the left leg; this index was shown to be biomechanically linked to the mean CG position along the ML axis (Genthon, Gissot, Froger, Rougier, & Perennou, 2008); 2) the mean CG position along the AP axis relative to the length of the feet. These two parameters allowed us to check the constancy of the CG positioning regarding the feet. Asymmetrical body-weight distribution and forward-backward leaning were indeed demonstrated as two factors interacting with postural steadiness (Rougier et al., 2001; Genthon & Rougier, 2005).

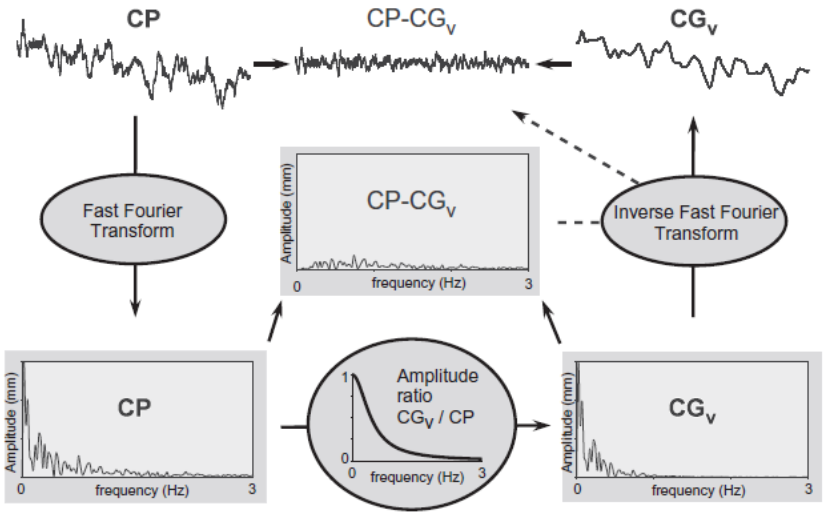

Fig. 1.
Synopsis of the different steps for the estimation of CP-CG_v and CG_v movements. The center-of-pressure trajectories can be depicted as a function of time along a given axis (top left). In order to obtain, along that axis, the center-of-gravity vertical projection, and consequently the CP-CG_v difference, a mathematical low-pass filter expressing an amplitude ratio between CG_v and CP as a function of the movement frequency, is used. With this aim in mind, the CP displacements are processed through a fast Fourier transform (FFT) in order to obtain the amplitude distribution as a function of the frequency. Once this CP spectrum is obtained, a multiplication with the aforementioned filter will give the CG_v spectrum and by subtraction the CP-CG_v spectrum (middle, left to right). At this stage, through an inverse FFT (iFFT), it is possible to return to the temporal domain and obtain CG_v, and consequently CP-CG_v movements (from Rougier and Caron, 2000).

The second method modeled the CG_v and CP-CG_v trajectories as a fractional Brownian motion (fBm, Mandelbrot & Van Ness, 1968). Briefly, this model provides a quantitative measurement of wiggle in a trajectory. Through this feature, the noninteger (fractal) dimension of a trajectory can be characterized. In this view, if a trajectory does not feel the whole place in a plane, its dimension will be ranged between 1 and 2. Due to the bounded nature of the displacements, the variograms computed from the CP displacements (i.e., mean square distances $<\Delta x^2>$ expressed as a function of increasing time intervals Δt) display two parts. The inflexion between the two parts can be interpreted as the spatiotemporal limit between the two control mechanisms called into play in this cyclic organization. It is possible, through fBm modeling of a CP trajectory, to assess the mean distance covered and the mean time interval from which the larger probability has to return the CP to a position that is more compatible with equilibrium principles, i.e., coming closer the CG_v.
The principle of the method, through which this transition can be objectively determined contrasts with the less objective method initially used by Collins and de Luca (1993) and is based on a comparison between experimental and average stochastic variograms (Rougier, 1999). For the CP trajectories, the complete stochastic process is characterized in the bi-logarithmic scaling by a one-slope straight line. The maximal distance between an experimental variogram and the one-slope straight line is thought to correspond to the Δt coordinate of the transition point. However, since the stochastic behavior, taken as a reference, is itself modified by the filters used to compute CG_v and CP-CG_v movements, scaling regimes related to average stochastic variograms over the same Δt must therefore be subtracted (Rougier & Caron, 2000). On the whole, for each elementary CP-CG_v and CG_v movement projected along the ML and AP axes, two scaling exponents (indexed as short and long latencies: H_{sl} and H_{ll}) as well as the spatiotemporal coordinates of the transition point ($<\Delta x^2>$ and Δt) were extracted.
As shown by the variogram, both CG_v and CP-CG_v displacements result from a combination of this set of parameters. To be more precise, the magnitude of the CP-CG_v movements mainly results from the level of

determinism in the exploratory process (H_{sl}) and the Δt from which the corrective process is initiated (in that case, the longer the Δt, the larger the $<\Delta x^2>$). Conversely, those of the CG_v movements mainly result from the delay from which the correction occurs, inferring more or less covered distances ($<\Delta x^2>$) and the level of deterministic activity during the corrective process (H_{ll}). In fact, modifications in these organization do not necessarily impact classical parameters such as variances, surfaces, mean velocities (Rougier, 2008). Separate analyses were performed along the ML and AP axes, since different muscular groups and control mechanisms are involved in the control of body motions and in the production of CP displacements along each of these axes, respectively (Winter, 1995; Winter, Prince, Frank, Powell, & Zabjek, 1996).
To evaluate the effects for the two MC and MN tasks, the results from the nine conditions were processed through a one-way ANOVA Friedman test with repeated measures. In these tests, the posturopgraphic parameters and the nine experimental conditions were the independent (within subjects) and dependant variables, respectively. Simple effects were then studied through nonparametric multiple comparison Dunn tests, with the first level of significance being set for both tests at $p<0.05$. Since the studied variables were shown to be unrelated in other past studies (Vuillerme & Nafati, 2007; Nafati & Vuillerme, 2011; Rougier, 2003), no adjustment for multiple tests was performed. The choice to use non parametric tests was motivated by their greater robustness, the reduced size of our sample and the multiplicity of parameters involved in these calculations.

3. Results

3.1. Classic parameters

The Friedman ANOVA for mean body-weight distribution and mean position along the AP axis expressed in relation to the length of the feet indicated statistically non significant results ($\chi^2(11,8)=4.73$ and 3.44; $p>0.05$, respectively). These results are shown in the upper bar charts of Fig. 2. The changes in the postural control strategies observed in this study (see below) therefore cannot be explained by such positioning factors.

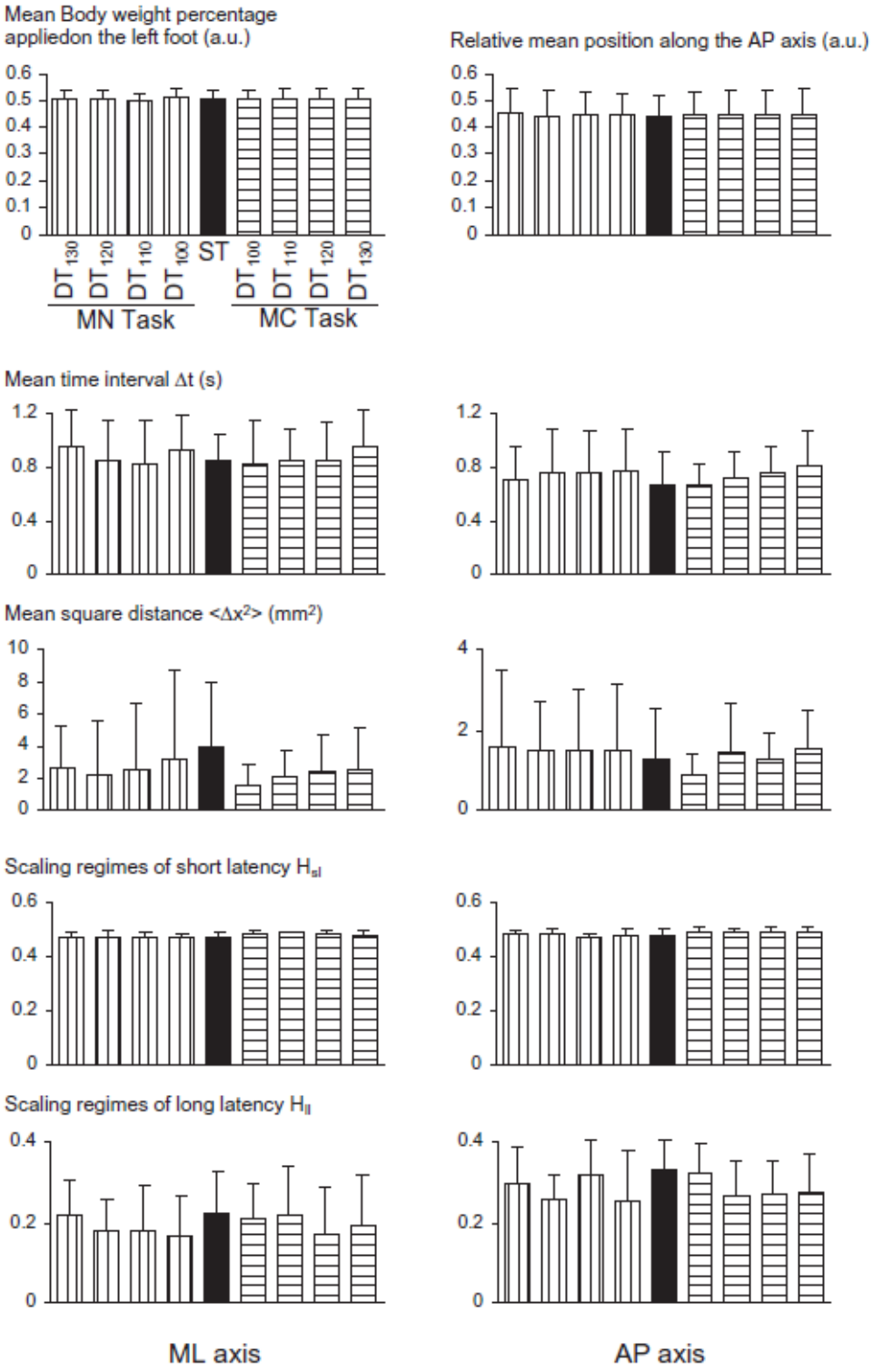

Fig. 2.
Bar charts representing, for the CG_v movements and the various conditions, mean (± s.d.) for the body-weight distribution and mean position along the AP axis relative to the length of the feet and for the parameters from modeling fBm computed along each ML and AP axis. The single-task (ST) and dual-task (DT) conditions are displayed in white with vertical hatchings, white with horizontal hatchings and black, respectively. Note the lack of a significant effect for all protocols and conditions.

3.2. Parameters from fBm modeling

Some statistically significant effects were found, which, interestingly, were only observed for the CP-CG_v movements (Fig. 3). Although the temporal coordinates of the transition points (Δt) appeared to remain unchanged throughout the conditions along both ML ($\chi^2(11,8)=5.90$; $p<0.05$) and AP ($\chi^2(11,8)=9.572$; $p<0.05$) axes, statistically significant effects were reported for the spatial coordinates $<\Delta x^2>$, but only along the ML axis ($\chi^2(11,8)=19.68$; $p<0.05$). The dual-task protocols significantly decreased the mean square distances $<\Delta x^2>$. The multiple comparison tests revealed significant effects between the DT_{110} condition of the MN task and the ST reference ($p<0.05$). However, along the AP axis, no significant trend was reported ($\chi^2(11,8)=9.43$; $p>0.05$). There was also non-significant effect for the spatial coordinates computed for the CG_v movements (Figure 1) (ML: $\chi^2(11,8)=10.26$; $p>0.05$; AP: $\chi^2(11,8)=7.76$; $p>0.05$).
Despite the above-mentioned change, no effect was observed for the scaling regimes of short and long latencies H_{sl} and H_{ll}. This applies for the CP-CG_v movements (Fig. 2) along ML (H_{sl}: $\chi^2(11,8)=11.02$; H_{ll}: $\chi^2(11,8)=13.36$; $p>0.05$ for both cases) and AP axes (H_{sl}: $\chi^2(11,8)=5.63$; H_{ll}: $\chi^2(11,8)=14.70$; $p>0.05$ for both cases) as well as for the CG_v movements (Fig. 2) along ML (H_{sl}: $\chi^2(11,8)=13.45$; H_{ll}: $\chi^2(11,8)=3.29$; $p>0.05$ for both cases) and AP axes (H_{sl}: $\chi^2(11,8)=10.28$; H_{ll}: $\chi^2(11,8)=13.94$; $p>0.05$ for both cases).

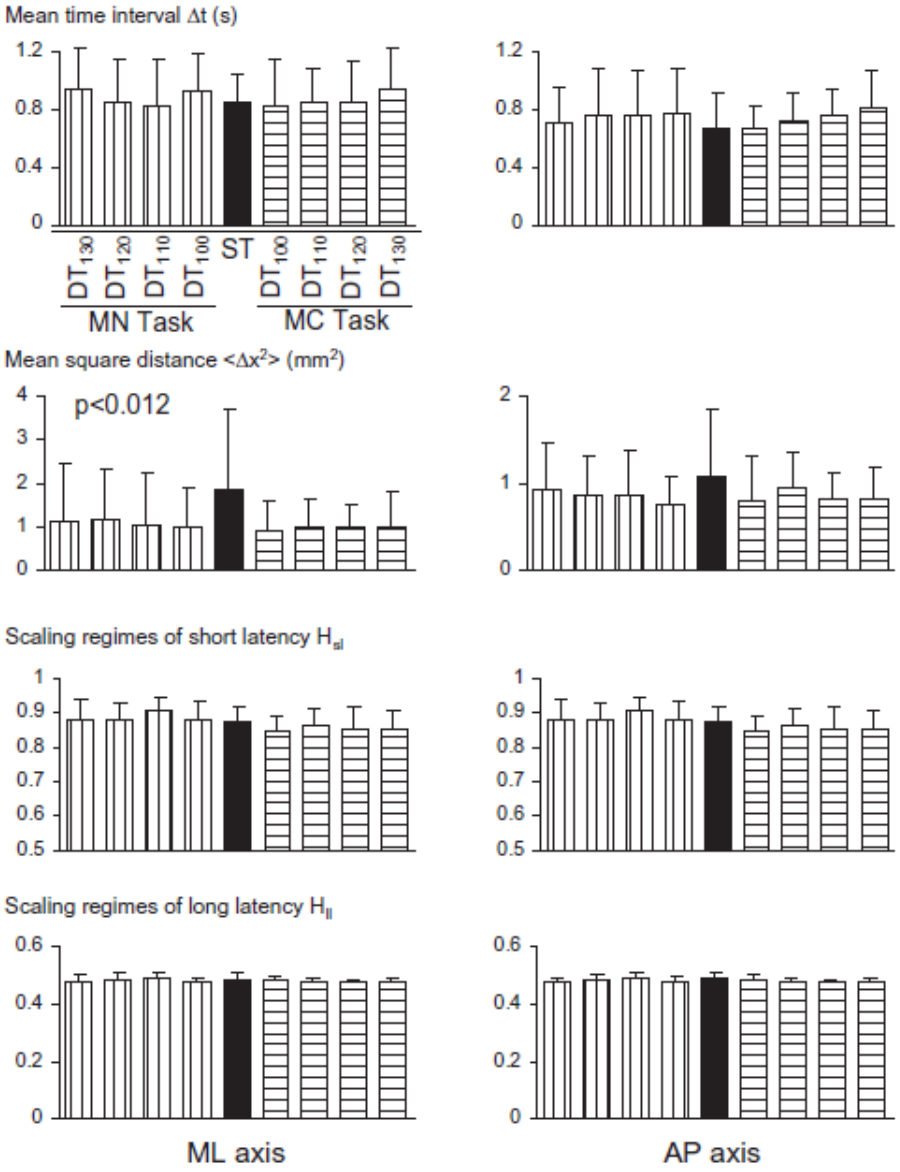

Fig. 3.
Bar charts representing, for the CP-CG_v movements and the various conditions, mean (± s.d.) for the parameters from modeling fBm computed along each ML and AP axis. The single-task (ST) and dual-task (DT) conditions are displayed in white with vertical hatchings, white with horizontal hatchings and black, respectively. Note the significant effect for the mean square distances along the ML axis.

4. Discussion

As stated in the introduction, our hypotheses were that 1) dual-tasks protocols should decrease predominantly the CP-CG_v movements. 2) Providing more time to solve the cognitive task should allow subjects to reduce CG_v movement. 3) The spatial navigation task, with a priori increased interferences at the brain level, should infer the larger postural effects, i.e. decreased CP-CG_v movements and possibly increased CG_v movements. On the whole, only the first hypothesis was validated by our results since dual-task protocols modified postural control organization by decreasing the mean square distances $<\Delta x^2>$ of the CP-CG_v movements but only along the ML axis. On the contrary, providing supplementary time to solve the

concurrent cognitive task had little effect on the postural control whereas the reported effects, observed for both cognitive tasks, thus appeared insensitive to the nature of the cognitive task.

4.1. Dual-task protocols modify postural control

The first interesting result is that DT tasks tend to change postural capacities, hence confirming the pioneering study (Fearing, 1925). Our study went further than usual paradigms (Fraizer & Mitra, 2008; Hwang et al., 2013; Pellecchia, 2003; Ramenzoni, Riley, Shockley & Chiu, 2007; Riley et al., 2003, Riley, Baker, Schmit, & Weaver, 2005, Simoneau, Billot, Martin, Perennou & van Hoecke, 2008; Swan, Otani, Loubert, 2007) 1) in disentangling the CP displacement into two components, each having specific biomechanical features and 2) by adapting for each subject the difficulty of the cognitive task to his/her maximal solving capacities. In our results, CG_v movements appeared to be not affected by the DT conditions, whereas CP-CG_v movements significantly decreased in DT conditions. The reduced $<\Delta x^2>$, observed in the DT protocols, must be viewed as expressing reduced CP-CG_v movements. Indeed, CP-CG_v movements behaving as random-walk over the longest time-intervals (H_{sl} being close to 0.5; Rougier & Caron, 2000), the mean spatial coordinate of the transition point $<\Delta x^2>$ is therefore a fair predictor of their magnitudes, as it can be seen from variograms plotting $<\Delta x^2>$ as a function of increasing Δt. This can be easily explained by the fact that there is an equal probability over this period for the CP-CG_v to drift away or, on the contrary, to return to its initial position. Taken together, it means that the postural performance remained unaffected, whereas the means called into play, i.e. muscular activity, tended to decrease when attention was diverted. This postural control feature, previously observed through EMG measurements (Simoneau et al., 2008) consists therefore in decreasing the forces the system has to handle to keep balance. As indicated by the Newtonian laws, the CG_v displacements in the horizontal plane are conditioned by horizontal accelerations and thus by differentiating CP and CG_v positioning. These decreased accelerations (forces), emphasized by smaller CP-CG_v amplitudes, can be viewed as an easier task to achieve and therefore should have led, all other things being equal, to decreased CG_v movements. Since such effect was not observed, it can be concluded that the control of the CG_v movements is in fact less efficient.
Considering the fBm modeling, it appears that the effects of attention, when available, mainly apply over the shortest time intervals, that is, during the exploratory phase of postural control (Riley et al., 1997), which sees the CP-CG_v component as principally controlled (Rougier & Caron, 2000). In contrast, no real modification was observed in the control of the CG_v movements, which appear to be mainly controlled during the longest time intervals (fig. 2). This result is in accordance with the data reported by Vuillerme and Nafati (2007) and Nafati and Vuillerme (2011) even though these authors found significant CP-CG_v decreases along both ML and AP axes during cognitive tasks.
To explain the discrepancy in the literature reports and in our results, we would like to suggest that the control of both CG_v and CP-CG_v elementary movements do not operate a priori through the same circuits at the CNS level. This view is reinforced by the fact that these two movements are not controlled over the same time intervals (Rougier & Caron, 2000). Indeed, as revealed by the fBm modeling, the CP-CG_v and CG_v components are controlled over the shortest and longest time-intervals, respectively. In other words, at a given time, only one elementary movements would be controlled. This independence between the two elementary movements effects is akin to the one observed in protocols such as visual feedback (Rougier, 2003). We need to recall that both CP-CG_v and CG_v movements contribute by definition to the overall measured CP displacements Furthermore, it is worth to note that CP-CG_v movements, because of their smaller amplitudes and higher frequency bandwidth, weakly influence spatial parameters such as surface in the CP displacements, whereas their incidence upon velocity or length parameters is much larger (Rougier, 2008).

4.2. Allowing more time to solve the cognitive task does not really affect postural control

According to the possibly sequential nature of the process, it was hypothesized at the onset that allowing more time to solve the cognitive task might have led to less interference. Considering past studies which focused on the influence of task difficulty on brain activation (Lamm, Bauer, Vitouch, Durec, Gronister &

Gstättner, 2001; Menon, Rivera, White, Glover & Reiss, 2000; Ohnishi, Matsuda, Hirakata, & Ugawa, 2006), increased time to solve the cognitive tasks was thought to result in a variability in brain activations and therefore some variable changes in the postural control behaviors. Our data on the whole showed no significant effect, even though there was a slight tendency of some parameters to go in that direction (in particular for the mean square distances $<\Delta x^2>$ which progressively slightly diminished along the ML axis with time intervals between successive instructions),. Hence, our data contrasted with past studies (Riley et al., 2003; Riley et al., 2005; Swan et al., 2007). The nature of the task and therefore the quantity of shared resources may better explain our results. Because both postural and cognitive tasks require attention resources, saturating one of them may prevent the attention resources from being fully involved in postural control. The lack of statistical result lets suggest that the nature of the cognitive task induces a larger effect than allowing more time to solve it.

4.3. Different structures and pathways can be concurrently used by the central nervous system to control upright stance

It is noteworthy that rather similar changes in postural control variables were observed in both MC and MN conditions, as compared to the baseline performance (ST condition). When elaborating our protocol, we attempted to involve specific cerebral areas in the cognitive task performance. One interesting result of the current study is that, despite using two cognitive tasks activating a priori different cerebral areas, the postural effects resulting from the two kinds of cognitive interactions were rather close. It can thus be hypothesized that the effects would not be linked to the specific neural circuits involved in the higher structures of the CNS in order to achieve balance maintenance but to the transitory incapacity of these higher structures to control postural movements. If language or distal upper limb movements take advantage to be controlled by cortical areas due to the precision required for achieving these tasks, this would not be necessary the case for the postural control. Indeed, as shown by somatotopic representations, the main muscles involved in postural control from the lower limbs and hips are poorly represented in the sensori-motor cortices. As a result, a control operating through the lower structures of the brain stem, although more automatic, could be beneficial in terms of stability. This view is akin with Ramenzoni et al. (2007) who stated that "only the amount of cognitive load impacts postural performance" and would be in accordance with previous studies in which subjects' attention was attracted toward saccadic eye movements, (external focus) (Rougier & Garin, 2006) or toward body stabilization (internal focus) (Vuillerme & Nafati, 2007). In our case, this interference would be suppressed due to the cortical saturation.
Lastly, the fact that the effects (DT vs ST conditions) were mainly seen along the ML axis may also highlight some differences in the organization in postural control between ML and AP axes. Biomechanical studies have indeed emphasized that two main mechanisms, each involving specific muscular groups, (the loading-unloading and pressure variation mechanisms), are involved in the production of CP displacements and therefore postural control (Bonnet, Cherraf, Szaffarczyk, & Rougier, 2014; Rougier, 2007; Winter et al., 1996). To be more precise, if the feet are positioned side by side, the hip muscles play a predominant role in securing the CP displacements along the ML axis whereas the ankle muscles play that role along the AP axis. The fact that the effects during DT tasks were more pronounced for the CP-CG_v movements along the ML axis but not concomitantly along the AP axis lets suggest at first view that the respective neural circuits involved in their control in both axes do not rely on the same structures. The specificity and the complexity of the ML control at the cortex level, as highlighted by EEG data for self paced whole body voluntary movements (Slobounov, Hallett, Cao, & Newell, 2008), may explain this trend.

5. Conclusion

Our results show that the nature of the cognitive task does not really impact the upright stance control, nor its difficulty. In fact, solely mobilizing attentional resources seems sufficient to induce changes in postural control Based on these data, one can suggest that a reduced attention induces two rather opposite phenomena: 1) on one hand, lower horizontal accelerations resulting from decreased neuro-muscular activities, which likely result from an automatic control involving subcortical structures, 2) on the other

hand a decreased capacity to control the CG_v movements due to shared circuits at higher levels of the CNS to control both postural and cognitive tasks. Each of these aspects impacting differently the parameters used to assess the complex CP displacements, assessing solely the postural control strategy on a CP measurement may not be sufficient to highlight the effects of a dual-task protocol.

Acknowledgments: The authors wish to thank L. Northrup for editing the text.

References

Brenière, Y. (1996). Why we walk the way we do ? *Journal of Motor Behavior*, 28, 291-298.

Brenière, Y., Do, M.C., & Bouisset S. (1987). Are dynamic phenomena prior to stepping essential to walking ? *Journal of Motor Behavior*, 19, 62-76.

Bonnet, C. T., Cherraf, S., Szaffarczyk, S., & Rougier, P. (2014a). The contribution of body weight distribution and center of pressure location in the control of mediolateral stance. *Journal of Biomechanics, 47*, 1603-1608.

Caron, O., Faure, B., & Brenière, Y. (1997). Estimating the centre of gravity of the body on the basis of the centre of pressure in standing posture. *Journal of Biomechanics*, 30, 1169-1171.

Collins, J.J., & de Luca CJ. (1993). Open-loop and closed-loop control of posture: a random-walk analysis of center of pressure trajectory. *Experimental Brain Research*, 95, 308-318.

Engle R.W., Tuholski, S., & Kane, M. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence and functions of the prefrontal cortex. In: A Miyake, P Shah, (Eds). *Models of working memory: mechanisms of active maintenance and executive control*. Cambridge University Press, Cambridge MA, USA, 102-134.

Fearing, F.S. (1925). Factors influencing static equilibrium. *Journal of Comparative Psychology*, 5, 1-24.

Fraizer, E.V., & Mitra, M. (2008). Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. *Gait and Posture*, 27, 271-279.

Genthon, N., Gissot, A.S., Froger, J., Rougier, P., & Perennou, D. (2008). Posturography in patients with stroke. Estimating the percentage of body weight on each foot from a single force platform. *Stroke*, 39, 489-491.

Genthon, N., & Rougier, P. (2005). Influence of an asymmetrical body weight distribution on the control of undisturbed upright stance. *Journal of Biomechanics*, 38(10), 2037-2049.

Hwang, J.H., Lee, C.H., Chang, H.J., & Park, D.S. (2013). Sequential analysis of postural control resource allocation during a dual task test. *Annals of Rehabilitation Medicine*, 37(3), 347-354.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Neurophysiologie Clinique – Clinical Neurophysiology*, 38,411-421.

Lamm, C., Bauer, H., Vitouch, O., Durec, S., Gronister, R., & Gstättner, R. (2001). Restriction of task processing time affects cortical activity during processing of a cognitive task: an event-related slow cortical potential study. *Brain Research Cognitive Brain Research*, 10, 275-282.

Maki, B.E., & McIlroy, W.E. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal* of Neural Transmission, 114(10), 1279-1296.

Mandelbrot, B.B., & Van Ness, J.W. (1968) Fractional Brownian motions, fractional noises and applications. *SIAM Review*, 10, 422-437.

Menon, V., Rivera, S.M., White, C.D., Glover, G.H., & Reiss, A.L. (2000). Dissociating prefrontal and parietal cortex activation during arithmetic processing. *Neuroimage*, 12, 357-365.

Nafati, G., & Vuillerme, N. (2011). Decreasing internal focus of attention improves postural control during quiet standing in young healthy adults. *Research Quarterly in Exercise and Sport*, 82(4), 634-643.

Ohnishi, T., Matsuda, H., Hirakata, M., & Ugawa, Y. (2006). Navigation ability dependent neural activation in the human brain: an fMRI study. *Neuroscience Research*, 55, 361-369.

Pellecchia, G.L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait and Posture*, 18(1), 29-34.

Ramenzoni, V.C., Riley, M.A., Shockley, K., & Chiu, C.Y. (2007). Postural responses to specific types of working memory tasks. *Gait and Posture*, 25, 368-373.

Riley, M.A., Baker, A.A., & Schmit, J.M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, 62, 191-195.

Riley, M.A., Baker, A.A., Schmit, J.M., & Weaver, E. (2005). Effects of visual and auditory short-term memory tasks on the spatiotemporal dynamics and variability of postural sway. *Journal of Motor Behavior*, 37, 311-324.

Riley, M.A., Wong, S., Mitra, S., & Turvey, M.T. (1997). Common effects of touch and vision on postural parameters. *Experimental Brain Research*, 117, 165-170.

Rougier, P. (1999). Automatic determination of the transition between successive control mechanisms in upright stance assessed by modelling of the centre of pressure. *Archives of Physiology and Biochemistry*, 107(1), 35-42.

Rougier, P. (2003). Visual feedback induces opposite effects on elementary centre of gravity and centre of pressure minus centre of gravity motions in undisturbed upright stance. *Clinical Biomechanics*, 18(4), 341-349.
Rougier, P. (2007). Relative contribution of the pressure variations under the feet and body weight distribution over both legs in the control of upright stance. *Journal of Biomechanics*, 40(11), 2477-2482.
Rougier P. (2008). What insights can be gained when analysing the resultant centre of pressure trajectory? *Neurophysiologie Clinique – Clinical Neurophysiology*, 38, 363-373.
Rougier, P., Burdet, C., Farenc, I., & Berger, L. (2001). Backward and forward leaning postures modelled by an fBm framework. *Neuroscience Research*, 41, 41-50.
Rougier, P., & Caron, O. (2000). Centre of gravity motions and ankle joint stiffness control in upright undisturbed stance modeled through a fractional Brownian motion framework. Journal of Motor Behavior, 32(4), 405-413.
Rougier, P., & Garin, M. (2006). La réalisation de mouvements de saccades oculaires affecte les stratégies de maintien de l'équilibre. *Neurophysiologie Clinique – Clinical Neurophysiology*, 36, 235-243.
Simoneau, E.M., Billot, M., Martin, A., Perennou, D., & van Hoecke, J. (2008). Difficult memory task during postural tasks of various difficulties in young and older people: a pilot study. *Clinical Neurophysiology*, 119, 1158-1165.
Slobounov, S., Hallett, M., Cao, C., & Newell, K. (2008). Modulation of cortical activity as a result of voluntary postural sway direction: an EEG study. *Neuroscience Letters*, 442, 309-313.
Swan, L., Otani, H., & Loubert, P.V. (2007). Reducing postural sway by manipulating the difficulty levels of a cognitive task and a balance task. *Gait and Posture*, 26, 470-474.
Tagaki, A., Fujimara, E., & Suehiro, S. (1985). A new method of statokinesigram area measurement : application of a statistically calculated ellipse. In : M Igarashi, O Black (Eds). *Vestibular and visual control on posture and locomotor equilibrium*, Karger, Basel, Switzerland, 74-79.
Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological Research*, 71, 192-200.
Winter, D.A. (1995). Human balance and posture control during standing and walking. Gait Posture 3, 193-214.
Winter, D.A., Prince, F., Frank, J.S., Powell, C., & Zabjek, K.F. (1996). Unified theory regarding A/P and M/L balance in quiet standing. *Journal of Neurophysiology*, 75, 2334-2343.
Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture*, 16, 1-14.