



Attentional cost in additional visual feedback protocols in healthy young subjects

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Abstract

Additional visual feedback (VFB) is a technique allowing improved postural stability in young healthy individuals despite an increased muscular activity, the two trends being assessed through center-of-gravity (CG_v) and differences between CG_v and center-of-pressure (CP) movements ($CP-CG_v$), respectively. These two opposing effects are likely explained by the respective contribution of automatic and voluntary controls and in turn the neural circuits involved. To specify these specific contributions, a dual-task protocol was set up, consisting in adding to VFB a navigation task performed at the maximum cognitive capacities of the subjects who were evaluated beforehand. Overall, the protocol comprises six conditions: three visual tasks (eyes open without VFB, VFB_{BW} based on body-weight distribution, VFB_{CP} based on CP displacements) associated with or without a cognitive task. Variances of $CP-CG_v$ and CG_v movements, along the mediolateral (ML) and anteroposterior (AP) axes, and parameters from fractional Brownian motion modeling (transition point coordinates and scaling regimes to assess the level of deterministic or stochastic activity) were used to assess the postural behaviors. The results show that during VFB_{CP} , the dual tasks protocol infers a decreased contribution of deterministic activity in $CP-CG_v$ movements, inducing decreased variances, and alters the correction of the CG_v over the longest Δt but nonetheless without changing CG_v variances. Disturbing the subject's attention during the VFB_{BW} condition induces decreased $CP-CG_v$ and CG_v movements along the ML and AP axes, respectively. These data demonstrate the high level of attention induced by VFB protocols. If the tonic postural activity, expressed through $CP-CG_v$ movements, decreases whatever VFB condition along both the ML and AP axes, the effects on CG_v movement appear to be mostly related to the additional information (BW or CP) provided. Overall, if too much voluntary control in upright stance maintenance is detrimental for the magnitudes of the $CP-CG_v$ movements, it appears beneficial for those of the CG_v movements. By emphasizing the role of automatic and voluntary controls in VFB protocols, these insights document the neural circuits involved in such protocols and specify their conditions of use.

Keywords Upright stance control · Healthy subjects · Additional visual feedback · Attention · Center-of-pressure · Center-of-gravity · Cognitive dual-task · Fractional Brownian motion modeling

Introduction

Postural control in upright stance must be viewed as a sensorimotor task requiring a variety of sensory information and precise motor commands. Providing to a standing subject additional visual feedback (VFB) of his pressure output, the center-of-pressure (CP) measured through a force platform

device, generally infers more efficient control and therefore better stability, as assessed through the vertically projected center-of-gravity (CG_v) movements (Rougier 2003; Boudrahem and Rougier 2009; Kennedy et al. 2013). As a result, VFB protocols are viewed as potential tools to improve standing-still capacities in rehabilitation protocols. Models such as fractional Brownian motion (fBm) have highlighted that this benefit originates principally from the increased determinism in the control of these CG_v displacements over the longest time intervals, i.e., during the corrective process (Rougier 2003). In other words, once a loss of balance is detected, the CG_v movements return to their previous equilibrium position more linearly. Less interesting since rendering more difficult the balance control, VFB, when applied

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in real time, also leads to increased determinism (and therefore their amplitudes) in the control of the other basic CP–CG_v movements (Rougier 2003; Szczepańska-Gieracha et al. 2012). These movements, described as an exploratory process (Riley et al. 1997), and solely controlled over the shortest time intervals (Rougier and Caron 2000), are mostly related to the activity of the postural muscles (Rougier et al. 2001). Since their amplitudes correspond to the horizontal acceleration communicated to the CG (Brenière et al. 1987), increasing their movements provokes greater difficulty handling the CG_v throughout the corrective process. As for any kind of movements, standing upright with the help of VFB relies on various neural circuits. However, to our knowledge, no study has attempted so far to document the structures of the brain involved in this peculiar task. Nonetheless, some appealing insights can be furnished by the fBm modeling concerning the temporal organization (i.e. the mean time delay from which the corrective process begins to operate) which remains unchanged compared to a condition with eyes open (Rougier 2003). As a result, it can be suggested that the same structures are involved in postural control, with or without additional VFB. Other indirect evidence might stem from the degree of control of the trajectory and therefore of the potential structures involvement. As initially proposed by Collins and de Luca (1993) through the fBm framework, the respective implication of stochastic (random) and deterministic (controlled) processes can vary according to the subjects or the experimental condition. One can therefore propose a link between the contribution of a given anatomical structure and the level of determinism in the movement control. This would explain why the increased control during VFB is due to the real-time characteristic of VFB. Indeed, when VFB is delayed, the above-mentioned effect tends to vanish (Rougier 2004, 2005, 2007a; van den Heuvel et al. 2009; Yeh et al. 2010). Fortunately, since these two effects (a CP–CG_v increase with a concomitant CG_v decrease) do not counterbalance each other, the gain of VFB in terms of stability or postural performance is largely positive.

Quite obviously, one efficient way to alter the level of determinism in postural control is to resort to dual-task (DT) protocols (for a review, see Lacour et al. 2008). Even though various cognitive tasks can be used, it seems that the key factor would be the disturbance of the subject's attention. Similar effects on postural control, consisting principally in a decrease of the amplitudes of the CP–CG_v movements, were indeed recently reported when simply modifying the attentional focus (Vuillerme and Nafati 2007) or using arithmetical calculation or navigation tasks (Rougier and Bonnet 2016). Considering the above-mentioned VFB specificities in terms of contributions of deterministic activities in postural control, we can first hypothesize that disturbing attention in VFB protocols should concomitantly infer less

determinism in that control which, in turn, should lead to decreased CP–CG_v and increased CG_v movements.

To better understand this interaction, it can be useful to consider both the complexity of the information fed back and the specificity of the effects in terms of axes. CP displacements are indeed a complex phenomenon implying the contribution of two basic mechanisms, loading–unloading and pressure distribution, each potentially predominant either along the mediolateral (ML) or anteroposterior (AP) axis (Winter et al. 1996; Rougier 2007b). For instance, in a side-by-side stance, loading–unloading and pressure distribution are principally responsible for displacing the CP position along the ML and AP axes, respectively. One of the advantages of the VFB technique is that information about only one mechanism can be provided, therefore leading to a specific modification in upright stance control (Rougier 2009). For instance, with a VFB solely based on weight-bearing control (VFB_{WB}), decreased CG_v movements were observed but only along the ML axis, i.e., the axis along which the loading–unloading mechanism is preeminent when the feet are positioned side by side. Interestingly, this is along this ML axis that the main effect of the DT paradigm occurs when feet are positioned side-by-side (Riley et al. 2003; Rougier and Bonnet 2016). Since strong evidence indicates that specific aspects of balance would be controlled by the cerebral cortex and high-level “cognitive” processing (Maki and McIlroy 2007), this ML effect could simply mean that the loading–unloading mechanism would be more controlled by cerebral loops than the pressure distribution mechanism mainly involved in AP sway control. Our second hypothesis would therefore be that an attention disturbance should predominantly affect the postural control operating along the ML axis.

Another interesting result of the recent study reported by Rougier and Bonnet (2016) is the role played, in DT protocols, by the difficulty of the cognitive task. By modifying the delay between the successive instructions, determined from the subjects' capacity evaluated beforehand, it was indeed shown that the postural effects were only seen with the shortest delays between each instruction. This result was akin to the observation made by Riley et al. (2003) on number rehearsal.

Considering that providing, through VFB, a complex CP movement resulting from the combination of the two control mechanisms can be viewed as more difficult than simply providing weight-bearing information, we lastly hypothesize that the postural effects, i.e. decreased and increased amplitudes of CP–CG_v and CG_v movements, respectively, should be greater in the former case.

Overall, the results of this study might be of interest to better assess the cognitive contribution of VFB protocols and therefore might specify their conditions of use.

Methods

Participants

Twelve young healthy male adults (mean age 21.4 ± 1.0 years; mean body weight 73.0 ± 8.6 kg; mean height 177.1 ± 6.3 cm) participated in the experiment. They gave written consent to the experimental procedure as required by the Helsinki declaration (1964) and the local ethics committee. None of the participants presented any known motor or visual problems, neurological disorders or vestibular impairment.

Posturography

The subjects stood barefoot on a double-force platform (Equi+, PF02) with the inner borders of the feet parallel, the heels 6 cm apart. The signals 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 CP was then computed and decomposed along the ML and AP axes. Rest periods lasting 32 s and about 5 min were allowed between each trial and each condition, respectively, and automatically managed by the recording software.

Experimental conditions

The protocol was built around three conditions performed without (single task ST) and with a concurrent cognitive task (dual task DT), resulting in a total of six conditions. In the reference (REF), subjects were asked to stand still on the force platform by staring at a fixed dot on the 17-in. screen of the turned-off monitor positioned in front of them. Two VFB conditions were also proposed: one consisted in the visualization of the weight-bearing variation, which was implemented by a vertical bar that was laterally displaced across the screen (VFB_{WB}) and one based on the display, in real time, of the resultant CP (VFB_{CP}). The display of the spot, which represents the CP displacements, was achieved with a scale of 5, indicating that the display on the screen was five times larger than the real CP displacements (Rougier et al. 2004). The software was set in such a way that the spot was always positioned at the center of the screen at the onset of each trial. To facilitate its tracking, only the last 64 positions (i.e., 1 s) were displayed. The horizontal displacements of the CP were displayed on the vertical screen from left to right and from top to bottom for the ML and AP components, respectively. For the two VFB conditions, a practice trial was always performed prior to measurements

to ensure that patients had mastered the relationship between their body motions and the spot displacements. Thus overall, six conditions (REF ST, REF DT, VFB_{WB} ST, VFB_{WB} DT, VFB_{CP} ST and VFB_{CP} DT) were randomly performed. Instructions differed depending on the conditions: in REF, subjects were asked to stand as still as possible, whereas in the VFB conditions, they were asked to reduce the spot displacements as much as possible.

The cognitive task, detailed in Rougier and Bonnet (2016), consists in performing a navigation exercise as quickly as possible through successive instructions given step by step and implemented in the force platform recording software. The cognitive task consisted in performing two-dimensional spatial displacements in a nine-cell square using four instructions (forward, backward, right and left) provided randomly. Subjects had to mentally imagine the displacements from a central position in the square and indicate, once the trial was over, what was the final position in the square. To help the subjects stay focused on the task, instructions were fed through headphones that were covered by a soundproof helmet. Before the postural measurements, pretests were performed by each subject to determine his maximum capacity, i.e., the shortest time required to perform the task. The best of the four trials of 20 successive instructions, which were given by pressing a keyboard button, was used for this purpose.

The result was then used to set the delay between the 40 successive instructions of the DT conditions, and therefore the trial duration. As a result, the duration of the trials was adjusted to the subject's own maximum capacities and thus varied across subjects. For each subject, the duration of the trials in ST conditions was set to match the duration of the DT. For all DT conditions, the validity of the final result, i.e., the final position with respect to the initial one (center of the nine-cell square), determined the inclusion of the trial in the data analysis. By doing so, we wanted to ensure that the cognitive task was effectively performed and, by using the shortest delays measured beforehand, that subjects focus as much as possible on the cognitive task resolution during the recording.

Since the mean time intervals computed from the pretests was 0.486 s (± 0.180) for the DTs, and the duration of each instruction lasts 0.3 s, it follows that the mean trial durations for the sample were 31 s (40×0.3 s + 39×0.486 s).

Signal processing

Because these CP displacements aimed at controlling CG_v displacements, and therefore accompanying them, it appears useful to separate the CP displacements into two basic components (Rougier and Caron 2000): the CG_v and the CP–CG_v displacements. CG_v movements were estimated from the CP displacements from a CG_v/CP ratio (Brenière 1996; Caron

et al. 1997). It was hypothesized that CP displacements operating at high frequencies would not incur appreciable CG_v movements. 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 the data, 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. All these steps are displayed in Fig. 1.

Once estimated, CG_v and CP– CG_v displacements were studied through two methods of analysis. The first one is based on two parameters: (1) the mean body-weight distribution over the left leg; this index was shown to be biomechanically linked to the mean CG_v position along the ML axis (Genthon et al. 2008); (2) the mean CG_v position along the AP axis relative to the feet length (mean AP/FL). These two parameters allow us to check the constancy of the CG_v 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 and Rougier 2005).

The second method modeled the CG_v and CP– CG_v trajectories as a fractional Brownian motion (fBm), a concept

developed by Mandelbrot and Van Ness (1968). This choice was indeed mandatory to retain parameters insensitive to trial durations, which changed across subjects, and to proceed to separate analyses along each ML and AP axis, since different muscular groups are involved in the control of body motions along each of these axes. Briefly, this model provides a quantitative measurement of wiggle in a trajectory. Through this feature, the non-integer dimension of a trajectory can be characterized. Interestingly, due to the bounded nature of the displacements, the variograms computed from the CP displacements (i.e., mean square distances $\langle \Delta x^2 \rangle$ 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. In other words, 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 to 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)

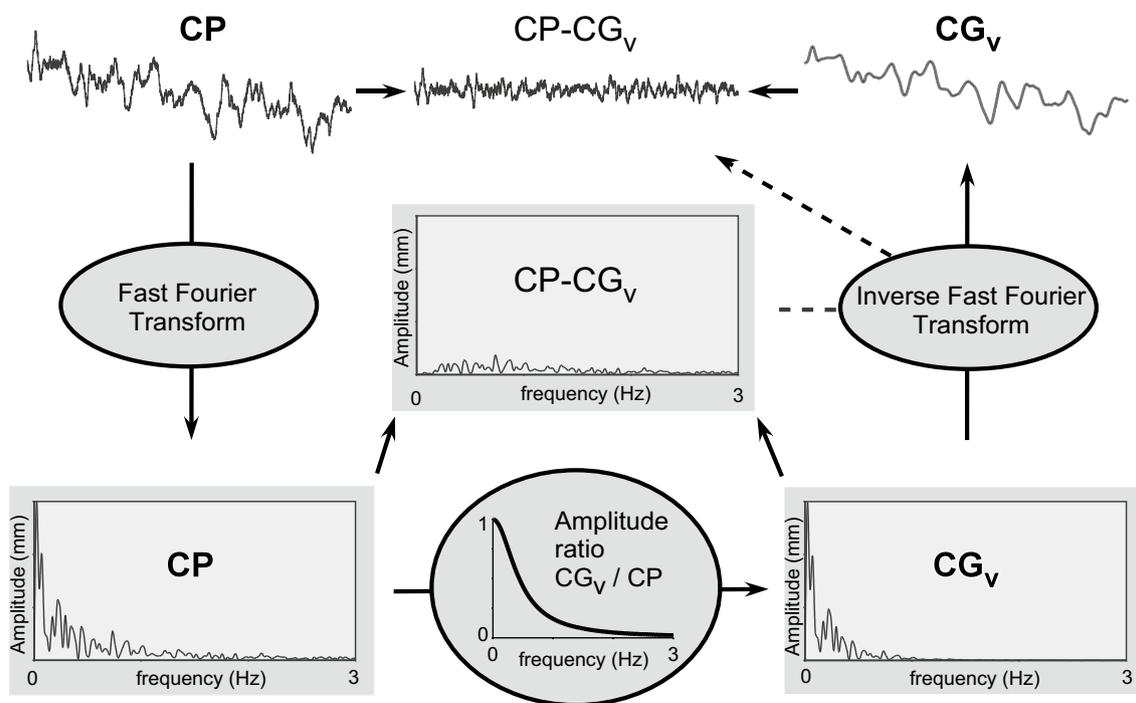


Fig. 1 Synopsis of the different steps for the estimation of CP– CG_v and CG_v movements. The CP trajectories can be depicted as a function of time along a given axis (top left). Along that axis, to obtain the CG_v , and consequently the CP– CG_v difference, a mathematical low-pass filter expressing 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)

and is based on a comparison between experimental and average stochastic variograms (Rougier 1999). For the CP trajectories, the complete stochastic process is characterized by a bi-logarithmic scaling by a one-slope straight line. The maximum distance between an experimental variogram and the straight line characterizing a complete stochastic behavior 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. On the whole, for each basic $CP-CG_v$ 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 ($\langle \Delta x^2 \rangle$ and Δt) were extracted.

The results from the six conditions were processed through a two-factors ANOVA (visual conditions and number of tasks) with repeated measures and with the partial Eta squared values η_p^2 for assessing the size effects. Simple effects were then studied through Newman–Keuls tests. For both tests, the first level of significance was set at $p < 0.05$. Since the variables studied were unrelated, no adjustment for multiple tests was performed.

Results

The mean and standard deviations for all parameters are displayed in Fig. 2. In addition, when ANOVAs were found to be statistically significant, factors and simple effects were also reported. For the sake of convenience, only the statistically significant effects are detailed in this “Results” section. It is noteworthy that most of the partial Eta squared values η_p^2 highlight small or medium effects.

Subjects’ orientation

The two parameters characterizing the orientation, i.e., the mean body-weight distribution and mean AP position expressed as a function of the feet length, are not modified by the protocol (Fig. 2g). This means that the reported effects are not related to modified strategies induced by leaning forward or backward and/or asymmetrical weight-bearing.

Cognitive task effects

The DT conditions infer a general trend consisting in decreasing the two basic $CP-CG_v$ and CG_v movements, as compared to ST conditions (Fig. 2a, f). The variances display statistically significant diminutions but with less emphasis for the former movements since significant effects were reported but only along the ML axis: $F(1,66) = 20.65$

($p < 0.001$; $\eta_p^2 = 0.24$). In contrast, for CG_v movements, a statistical effect was found for both ML [$F(1,66) = 4.21$; $p < 0.05$; $\eta_p^2 = 0.06$] and AP [$F(1,66) = 21.87$; $p < 0.001$; $\eta_p^2 = 0.25$] axes.

These results are further explained by the fBm modeling. As seen in Fig. 2c, the reduced $CP-CG_v$ movements are characterized by shorter mean square distances (Δx^2) (spatial co-ordinates of the transition point) along the ML axis [$F(1,66) = 17.95$; $p < 0.001$; $\eta_p^2 = 0.21$] and less control over the longest Δt (Fig. 2e): [$F(1,66) = 7.50$; $p < 0.01$; $\eta_p^2 = 0.10$]. For the reduced CG_v movements along the ML axis, one can see through Fig. 2j that the DT protocols mainly impact the H_{ll} scaling regimes [$F(1,66) = 5.74$; $p < 0.05$; $\eta_p^2 = 0.08$], especially during the VFB conditions, which tend to increase, hence indicating a deterioration in the control of these movements over the longest Δt . In contrast, it is the enhanced control over the longest Δt [$F(1,66) = 10.94$; $p < 0.01$; $\eta_p^2 = 0.14$] which explain the decrease of the CG_v movements along the AP axis (Fig. 2j).

Visual effects

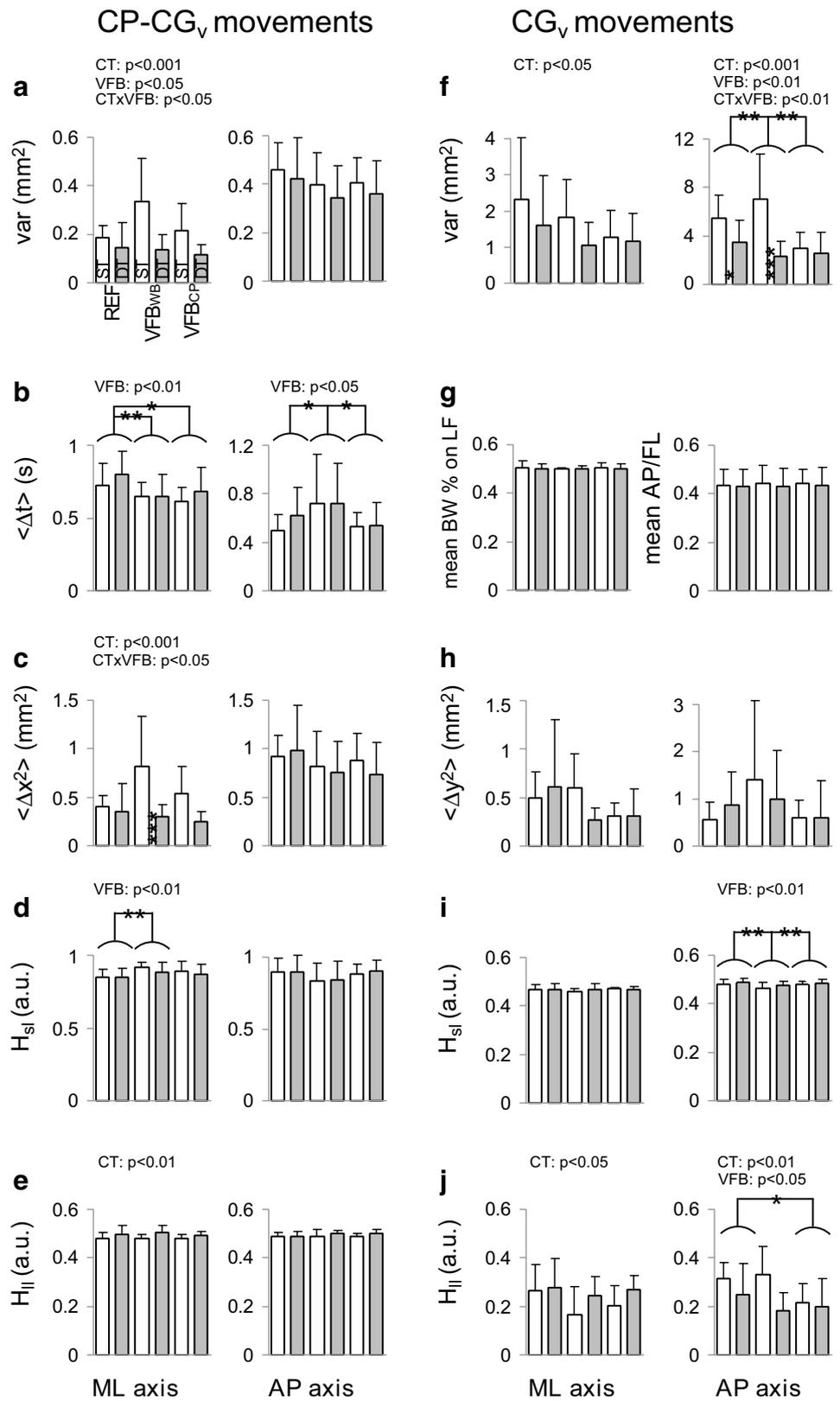
Modifying the visual information interacts with the variances of the CG_v movements [$F(2,66) = 5.66$; $p < 0.01$; $\eta_p^2 = 0.15$] along the AP axis and those of the $CP-CG_v$ along the ML axis [$F(2,66) = 3.62$; $p < 0.05$; $\eta_p^2 = 0.10$]. Indeed, as indicated by the bar charts in Fig. 2f, providing VFB determines increased CG_v movements, in particular on BW distribution (VFB_{BW} conditions), as compared to the REF and VFB_{CP} conditions. However, the statistical analysis was unable to reveal simple effects for the $CP-CG_v$ movements along the ML axis.

fBm modeling allows us to specify the origin of these effects. Along the ML axis, an increased control of the $CP-CG_v$ movements over the shortest Δt , expressed by the H_{sl} scaling exponents, can be observed (Fig. 2d) for the VFB_{BW} condition [$F(2,66) = 4.92$; $p < 0.01$; $\eta_p^2 = 0.13$]. This, in turn, might explain the shortest delays of the onset of the corrective process $\langle \Delta t \rangle$ (Fig. 2b) [$F(2,66) = 4.99$; $p < 0.01$; $\eta_p^2 = 0.13$]. Along the AP axis, providing additional VFB on BW increases the time delay of the onset of the corrective process ($\langle \Delta t \rangle$) [$F(2,66) = 3.60$; $p < 0.05$; $\eta_p^2 = 0.10$], whereas no statistical difference, as seen in Fig. 2 is noted for the control over the shortest latencies (H_{sl}) of the $CP-CG_v$ movements. The effect reported for the scaling regimes of longest latencies (H_{ll}) for the CG_v movements is explained by a better control, i.e., more deterministic, during the VFB_{CP} condition (Fig. 2j).

Interaction effects

Three interactions were reported through the statistical analysis. For the $CP-CG_v$ movements, the interaction

Fig. 2 Bar charts representing, for the CP–CG_v and CG_v movements and the various conditions, mean (\pm SD) for the variances and for the parameters from fBm modeling computed along each ML and AP axis. The single-task (ST in white) and dual-task (DT in gray) conditions are displayed side by side for all visual conditions. When statistically significant, the associated probability is given for the ANOVAs performed for each factor (*CT* cognitive task; *VFB* visual feedback; *CT* × *VFB* interaction). Post-hoc analysis is displayed through bars and stars above the bar charts for the *VFB* factor and between columns for the interaction: **p* < 0.05; ***p* < 0.01; ****p* < 0.001



concerns the variances along the ML axis [$F(2,66) = 3.37$; $p < 0.05$; $\eta_p^2 = 0.09$] but with no simple effects (Fig. 2a). The second one indicates some effects for the variances of the CG_v movements along the AP axis [$F(2,66) = 5.93$; $p < 0.01$; $\eta_p^2 = 0.15$] with statistically significant differences between ST and DT for only REF and VFB_{BW} conditions (Fig. 2f). The last one involves the mean square distances $\langle \Delta x^2 \rangle$ of the CP– CG_v movements computed along the ML axis [$F(2,66) = 4.03$; $p < 0.05$; $\eta_p^2 = 0.11$]. The simple effects analysis highlights differences between ST and DT protocols only for the VFB_{BW} condition (Fig. 2c).

Discussion

The results have demonstrated that additional feedback effects could be markedly modified when the subjects' attention was disturbed. This feature underlines the role played by the neural circuits of the cerebral cortex and high-level cognitive processing in this postural task (Maki and McIlroy 2007). To our mind, two main findings are worth noting. Firstly, disturbing the subjects' attention interacts in both exploratory and corrective mechanisms involved in upright stance maintenance, leading to less determinism in the recorded trajectories. Secondly, when additional information is provided on body movement control along a single axis (BW distribution along ML), significant changes also occur in the control of the movements intervening along the orthogonal AP axis.

Excessive determinism in postural control due to additional feedback is alleviated in dual tasks

Previous studies conducted on the topic showed that displaying the resultant CP displacements in real time induces increased CP– CG_v movements, especially along the ML axis, and reduced CG_v movements, along both the ML and AP axes (Rougier 2003). With fBm modeling, these opposite trends were both explained by the increased contributions of deterministic activities in the control of the two basic trajectories. This enhanced determinism induces increased H_{sI} and decreased H_{lI} values over the shortest and longest Δt , respectively. The enhanced control of CP– CG_v movements in turn infers enhanced mean square distances $\langle \Delta x^2 \rangle$, even though a shorter delay for the onset of the corrective process (Δt) is noted, in particular along the ML axis. Interestingly, despite greater horizontal accelerations, the distances covered by the CG_v movements at the onset of the corrective process are nonetheless decreased along this ML axis. Overall, this modification in postural control, especially what was observed for the VFB_{CP} conditions, confirms the previous studies on this topic (Rougier 2003).

The addition of a DT to the VFB control appears to alleviate the contribution of deterministic processes (enhanced H_{sI} and H_{lI} values) in both CP– CG_v and CG_v movements, but only along the ML axis and over the longest Δt (Fig. 2e, j). As a result, when a DT is performed, the beneficial effect of VFB tends to vanish, since, as already stated, the increased control over the longest Δt is the main outcome of these VFB protocols. Conversely, along the AP axis, the DT effect is mainly seen for the REF conditions with reduced determinism in the control operating over the longest Δt for the CG_v movements (Fig. 2j). Providing additional VFB in that case does not affect the degree of control. Note that due to the behavioral specificity induced by the VFB_{BW} condition, only the REF and VFB_{CP} conditions can be compared. In this case, a slight tendency is still seen for the control of the CP– CG_v movements over the shortest Δt , whereas the dual-task effect, this time, is mainly reported for the REF condition. In other words, our dual-task protocols mainly affect the REF and the VFB_{CP} conditions along the ML and AP axes, respectively.

From a physiological point of view, these results highlight the likely role played by the higher and lower structures of the CNS for controlling upright stance. In the hierarchical organization initially proposed by Hughlings-Jackson (1873), where each successively higher level controls more complex movements, the underlying neural circuits involved in both automatic and voluntary movement control are henceforth well known (Drew et al. 2004). To be more precise, that there is a proportion of the circuits involving motor cortex projections on both spinal motor and interneurons and on brain stem nuclei (reticular formation) looks realistic. In this way of thinking, attention disturbance would diminish the excitatory inputs over the brain stem nuclei, which would in turn decrease the muscular tonic drive, hence explaining the decrease of the CP– CG_v movements. The neurons of the pontomedullary reticular formation indeed make a huge contribution to the regulation of postural tone during standing (Mori 1987). The observed effects on the lower capacity of the CNS to control the CG_v movements with VFB, which from fBm modeling is only achieved over the longest Δt , may stem from competition for central processing resources. This lower muscular tone can also be viewed as the result of a shift, due to attentional disturbance, from a voluntary to a more automatic control. This automatization of postural control was proposed for explaining their results in young healthy adults by Bernard-Demanze et al. (2009). Recently, Richer et al. (2017) have hypothesized this possibility to explain their decreased sways during DT protocols based on arithmetical calculations.

These results appear to be in accordance with a recent study by Yeh et al. (2014), even though their cognitive task, based on an arithmetical resolution, was performed at a much slower rate than the one used here. Allowing large

amounts of time to solve the cognitive tasks in such protocols largely impacts the size of the interference (Rougier and Bonnet 2016). Despite differences in the two approaches for analyzing the CP data, their 0.3-Hz cutoff frequency is close to the biomechanical principle retained here to extract the basic movements of CG_v and $CP-CG_v$, making it possible to compare the two studies.

Providing additional VFB on one control mechanism modifies the control of the non-displayed mechanism

At the onset, since the VFB effects, consisting in an increased contribution of deterministic processes, were principally reported for movements occurring along the ML axis (Rougier 2003), our objective was to assess whether disturbing the attention of the subject could alter this effect. The results indicate contrasting effects for the two basic $CP-CG_v$ and CG_v movements. Firstly, a partial visual display of the BW distribution (VFB_{BW} condition), infers a better stability along the ML axis, as expected, as assessed by the variances of the CG_v displacements (Fig. 2f), but with a drastic increase of the $CP-CG_v$ movements (Fig. 2a). On the other hand, along the AP axis, the CG_v movements tend to increase (Fig. 2f), whereas those of the $CP-CG_v$ tend to decrease (Fig. 2a). Overall this postural behavior is akin to our previous study on this topic (Rougier 2009). The attention disturbance inferred in this VFB_{BW} condition decreased amplitudes for all movements and along the two axes. However, it is worth noting that the largest effects intervene upon the movements that were the more disturbed by VFB, as compared to the REF condition, i.e., the $CP-CG_v$ movements along the ML axis and those of the CG_v along the AP axis. These changes in the postural control strategies along the ML axis are further explained by the fBm modeling, which shows increased determinism for the H_{sl} values over the shortest Δt with VFB (Fig. 2d), a feature abolished by the DT protocol. This observation therefore highlights the role played by the attention process in these effects related to the display of partial information. Interestingly, the degrees of stability obtained for the CG_v movements along this AP axis are well below the scores observed for the REF condition and are close to those reported for the whole VFB_{CP} condition (Fig. 2f). This observation underlines the dual and independent process through which the two mechanisms, i.e., loading–unloading and pressure variation, operate.

Conclusion

Our data have confirmed that attention disturbance alters the postural strategies resulting from additional VFB. It firstly alters the tonic postural activity, expressed through

$CP-CG_v$ movements, whose amplitudes diminish over the two ML and AP axes. An effect on CG_v movement can also be observed, but it seems related to the information provided to operate the correction over the longest Δt . Overall, our three hypotheses were confirmed since disturbing attention in VFB protocols infer (1) less determinism in the control of the $CP-CG_v$ and CG_v movements, leading to decreased and increased amplitudes, respectively; (2) mainly affect the control operating along the ML axis, but mostly for the $CP-CG_v$ movements and finally (3) determine greater effects in the VFB_{CP} than in the VFB_{BW} condition, especially for the CG_v movements.

These features may be of interest in a neuro-rehabilitation perspective. Even though the value of VFB protocols in this field is still questioned (see Rougier and Boudrahem 2010), the subjects' variable capacity to focus on the information provided visually might likely explain the heterogeneous postural behaviors in these hemiparetic patients. In addition, the relative capacity of the CNS to rely on automatic control, which can potentially be affected by age, can also be a confounding factor.

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interest.

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