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Published in:
Gait & Posture

Publication date:
2001

Citation for published version (APA):
Dault, MC., Mulder, TW., & Duysens, J. (2001). Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. *Gait & Posture*, *14*(3), 248-255. [PII S0966-6362(01)00130-8].

ELSEVIER

Gait and Posture 14 (2001) 248–255

GAIT & POSTURE

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Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations

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Accepted 19 February 2001

Abstract

Postural control during normal upright stance in humans is a well-learned task. Hence, it has often been argued that it requires very little attention. However, many studies have recently shown that postural control is modified when a cognitive task is executed simultaneously especially in the elderly and in the presence of pathology. This study examined postural control modifications when a cognitive task of varying difficulty levels is added. Postural stance difficulty was also varied. Results from this study suggest that a generalized capacity interference may occur due to the larger interference found with the addition of a cognitive task in the more novel and difficult postural task. Because the performance of the cognitive task was tapered by a speed-difficulty trade-off, it was not possible to determine whether a change in the level of difficulty of the cognitive task occurred and if it would produce larger dual-task interference.

Keywords: Postural control; Centre of pressure; Attention

1. Introduction

Postural control during normal upright stance in humans is a well-learned task. Hence, it has often been argued that it requires very little attention [1,2]. Postural control is subserved by numerous neural pathways at spinal and supraspinal levels that constitute elementary reflexes and initially learned synergies which form the basis for fast responses to body perturbations [3]. These reflexes and synergies provide a continuous parametric control of gain and phase of feedback sensorimotor loops directed at maintaining a certain state of equilibrium [4]. Therefore, this lower level mode of control is usually regarded as independent of attention demands because it requires only a minimum of computational activity [5]. However, recent research has shown that dual-task paradigm involving increased cognitive demand can modify postural control [6–10].

The involvement of cognitive processes in the control of posture first became apparent when considering the role of feedforward control in adaptation to motor goals. It was shown that prior knowledge affected both the timing of anticipatory postural adjustments when comparing unexpected to self-initiated arm movements [11–13], as well as the magnitude of the postural responses to externally induced body perturbations by modifying 'central set' based on prior experience [14]. Still, it was hypothesised that cognitive influence on postural control was discontinuous, that is, during short periods of adaptation to new equilibrium states, e.g. during an alteration of support-surface configuration [15,16]. Even in such instances, because of the low attentional demands needed to maintain postural control using pre-structured synergies, marked vulnerability of postural activity to cognitive task performance on the basis of central capacity interference was not likely to occur [17,18].

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0966-6362/01/$ - see front matter
PII: S0966-6362(01)00130-8

However, in recent years, the automaticity of postural control has been challenged. Kerr et al. [19] found that the performance of a cognitive (visuo-spatial) task was modified when participants were asked to simultaneously execute a difficult balance task. Also, changes in postural sway have been found when participants are asked to execute a cognitive task indicating that attention may play a role in the control of posture [8,20–22]. Dependency on attentional processes seems even more apparent when the central nervous system (CNS) is impaired such as in elderly participants [6–8,23–26] and in the presence of pathology [9,10,22].

If we consider that motor control and cognitive processing are carried out in parallel by using time-sharing strategies, the difficulty and novelty of the tasks will have a great impact on how well both types of information processing can be performed simultaneously [27]. If the level of difficulty of one of the two tasks is increased, it may be reflected by a reduction in the performance quality of the other task. Since shoulder width stance is a well-learned skill it should require little attention [27]. On the other hand, if the postural task is more difficult, we could hypothesise that the interference caused by simultaneous cognitive processing, may be greater since the primary task will require more attention. Inversely, if the cognitive task difficulty is increased, less attention resources may be available for postural control and an increased interference may also occur. To test the validity of these hypotheses, this study addresses the question if and to what extent postural control can be influenced by cognitive task performance even in healthy young adults balancing on different support-surface configurations.

In addition to quiet upright standing on a firm and flat support surface (shoulder width stance), we examined standing on two other support-surface configurations in order to interfere with the efficacy of commonly employed postural strategies. Firstly, participants were requested to balance on a pair of seesaws, thus complicating the utilisation of vertical ground reaction forces through ankle torque generation to control antero-posterior body sway [5,18]. This manipulation was believed to require only a change in parameterisation (timing and gain) of well-developed synergies mainly in the sagittal plane. In order to increase the level of difficulty and to add a novelty aspect, we asked participants to also stand in a tandem stance on the same seesaws, thus completely eliminating the intrinsic mechanical stability of lateral balance which is normally provided by double-limb support in the frontal plane. By having them stand on the seesaws, we hoped to also complicate the control of antero-posterior sway by reducing the efficacy of ankle mechanisms in the sagittal plane. However, in a tandem position, bipedal stability was now available in this plane. Hence, tandem seesaw stance was primarily expected to induce a change in balance strategy towards the generation of high frequency ankle torques working in the frontal plane. Because this control mechanism is less practised in daily activities, a clear dual-task effect on lateral sway control was predicted for this task.

Three levels of difficulty of the cognitive task were chosen. The Stroop task was selected because its performance requires a considerable amount of attention even after many repetitions and because it comprises three discrete levels of complexity [28]. It was assumed that the three Stroop tasks, with increasing level of difficulty, would demand an increasing amount of attentional capacity and, therefore, would increasingly interfere with postural control especially during tandem seesaw stance.

2. Methods

2.1. Participants

Twenty-four individuals, 12 females and 12 males, aged between 20 and 40 years old, participated voluntarily in this study. The experimental group consisted of students, therapists, as well as technical and civil personnel of a rehabilitation clinic. Participants with more than average balance skills acquired by special activities such as dancing and gymnastics were not included. Every participant had normal or corrected-to-normal visual acuity, as well as unimpaired colour perception.

2.2. Equipment

Postural sway was measured by asking participants to stand on a dual-plate force platform that recorded vertical ground reaction forces. Force signals were amplified and led through first order low-pass filters with a cut-off frequency of 30 Hz. After a 12-bit AD-conversion, they were stored into a personal computer at a sampling rate of 60 Hz. In order to calculate the moment-of-force, the point of application of the resultant of the ground reaction forces in a two-dimensional transverse plane was determined for each sample with a maximum error of ± 1 mm in both directions. The coordinates of this centre of pressure (CP) were passed through a digital low-pass Fourier filter with a cut-off frequency of 6 Hz to eliminate high-frequency components due to noise or tremor. A remote-controlled slide projector was used to project samples of the Stroop task onto a white projection screen, which was placed 1.5 m in front of the platform.

2.3. Balance task

Participants were asked to maintain postural control while standing in three different support-surface configurations: (a) shoulder width stance where each foot was positioned against a foot frame and placed on one of the two force plates (distance between the medial sides of the heels was 8.4 cm with an external rotation angle of 9°) (shoulder width); (b) shoulder width stance while standing on two individual seesaws each placed on one of the force plates (shoulder–seesaw); and (c) tandem stance (heel-to-toe position) while standing on the seesaws (tandem–seesaw). Balance tasks are illustrated in Fig. 1.

The seesaws used in the latter two balance tasks consisted of wooden platforms (30 × 10 cm) with a curved base (radius 40 cm). When parallel to the ground, the line of contact of the seesaws with the ground was at a distance of 11 cm from the top and was located asymmetrically at 40% length (12 cm) from the rear (see Fig. 1). At the bottom of each seesaw, a longitudinal groove was made to guide its rolling motion along a rail fixed to the platform in order to prevent rotations. Foot placement on the seesaws was individually adjusted in such a way that the ankle joint was slightly behind the rotation point of the seesaw in the antero-posterior (AP) direction (see Fig. 1). As for the tandem–seesaw stance task, the direction of orientation of the participant was rotated 90° to the right so that, again, each seesaw could be placed on separate force plates. Sufficient space (3 cm) was left between the seesaws to permit free rolling movements. Every participant selected their preferred anterior foot. Once selected, the anterior foot was kept constant during the rest of the testing session.

Participants were instructed to stand as still as possible with their hands clasped behind their back for a period of 22 s. This recording length was chosen due to the difficulty of the postural stances. During the tandem–seesaw stance, they were instructed to bear at least 35% of their body weight on the anterior foot, which was exemplified during the practice trials by means of auditory feedback providing information about weight bearing on each leg. If a balance task was performed without a concurrent Stroop task (single-task condition), a visual reference was projected onto the screen in the form of a white upright cross (10 cm wide and 50 cm long) on a dark background, yet no specific instructions were given with respect to visual attention. This visual structure was added to provide sufficient visual reference to use optic flow.

2.4. Stroop task

Three modified (shortened) versions of the Stroop task were used — the word card, the colour card, and the colour-word card — each consisting of 25 items randomly arranged in a 5 × 5 matrix of evenly spaced rows and columns. The word card (WC) was made of colour names printed in black, whereas the colour card (CC) was made of rectangular blocks printed in different ink colours. The colour-word card (CWC) consisted of colour names that were incongruent with the printed ink colour, for instance the word 'GREEN' printed in yellow. Except for the word card, the same four colours were used: yellow, green, red and blue. Every card was projected onto a white projection screen at eye level with a size of approximately 70 cm (width) × 30 cm (height). In this way, the projection cone formed a visual angle with the participant's head of approximately 26° in the horizontal plane and 14° in the vertical plane.

Participants were instructed to read the colour name on the word card and name the colour of the block on

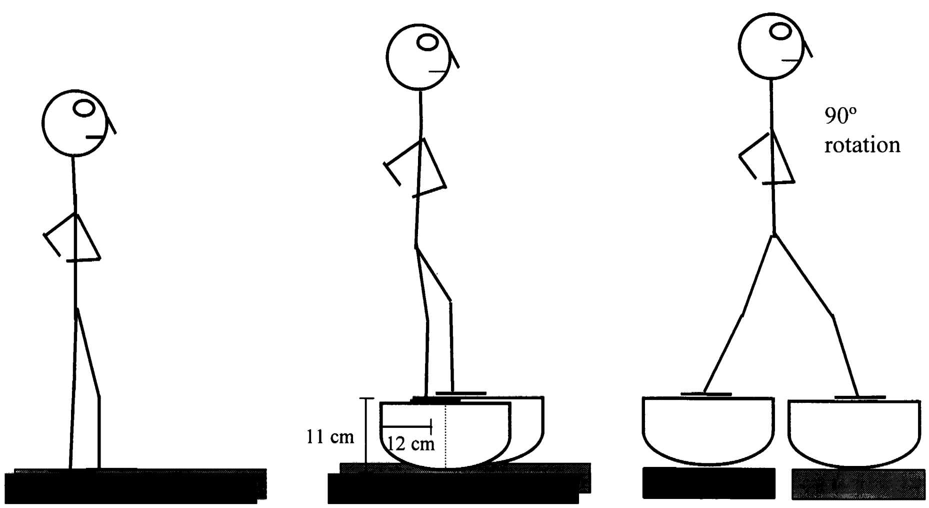

Fig. 1. A schematic illustration of the three postural stances with participants standing on the force platform: (a) shoulder width stance, (b) shoulder–seesaw stance, (c) tandem–seesaw stance; during the tandem stance the participants were rotated 90° to the right with respect to the position shoulder width stances.

the colour card, from the left to the right and from the top downwards. As for the colour-word card, the colours of the inks must be named while suppressing the strong tendency to read. With each task, participants were requested to complete as many items as possible for a period of 22 s. If participants completed the last (25th) item before the end of the trial, they were instructed to start again with the first item. If noticed by the participant, errors had to be immediately corrected.

2.5. Procedures

Participants performed a single task trial and three dual-task trials (with the three Stroop tasks) for each balance task. In addition, the Stroop task was performed in a sitting position in order to compare the effects of each balance task on the performance of the Stroop task. In sum, three balance levels were obtained (shoulder width, shoulder–seesaw and tandem–seesaw) and four Stroop task levels [no task (NT), WC, CC, CWC]. All possible permutations were executed (4 cognitive conditions $\times$ 3 balance conditions $=$ 12 permutations) and presented in a random fashion to the participants.

Before starting the measurements, participants received verbal instructions about the different Stroop and balance tasks. Each of the three Stroop tasks was then practised three times. Thereafter, the tandem–seesaw was practised for a short period to select the anterior foot and in order to learn the adequate weight bearing posture with the use of auditory feedback.

In addition, each condition was practised once, immediately before the performance of three consecutive identical trials that were recorded and analysed. After each trial, a 1-min rest was permitted. In the nine dual-task conditions, the Stroop card was projected immediately at the start of the balance registration. In the three single-task conditions, the visual reference was also available from the start of the registration. The total procedure lasted, including instructions and practice trials, approximately 90 min.

2.6. Data analysis

For every 22 s of balance task registration, the first 176 and last 120 of the 1320 samples (22 s at 60 Hz) were discarded in order to exclude the possibly undesired effects found at the start and end of each trial. Thus, 1024 samples were fed into a filtering process using a Fourier analysis technique. Then, the root mean square was derived from the CP displacement (amplitude or RMS Acp) and velocity (RMS Vcp) was determined after a first order differentiation in both AP and LAT directions separately. From these parameters, the mean frequency (Fcp) was estimated following the equation proposed in Geurts et al. [29] ($F\text{cp} = V\text{cp}/(A\text{cp} \times 4 \times \sqrt{2})$). Because Acp is mainly influenced by the lower frequency large-amplitude components reflecting the displacements of body mass, it was regarded as a measure of body sway. The frequency calculation and the amplitude measure enabled us to examine the changes in stiffness, which may be characterised by an overall increase in frequency and decrease in amplitude [30,31]. If the interaction between frequency and amplitude remains inversely proportional, velocity of the CP should remain stable indicating that participants maintained the same level of postural stability, although possibly using a different degree of stiffness strategy. On the other hand, if this relationship does not remain proportional, we can expect a change in CP velocity indicating a change in postural stability between experimental conditions. For each Stroop task condition, the number of items completed and errors in the 22-s registration period were recorded to monitor performance of the secondary task.

2.7. Statistical analysis

Statistical analysis was conducted on the average value of the three consecutive identical trials in order to reduce intrasubject variability. Postural control variables (Acp, Fcp and Vcp) were analysed using a mutlivariate analysis of variance (MANOVA) with Balance as the first factor (shoulder width, shoulder–seesaw and tandem–seesaw) and Stroop as the second factor (NT, WC, CC, CW) with repeated measures on both factors. Stroop task performance was also analysed using a Balance (sitting, shoulder width, shoulder–seesaw and tandem–seesaw) $\times$ Stroop (WC, CC, CW) analysis of variance with repeated measures on both factors.

3. Results

3.1. Balance data

A main balance effect was found for all variables (Acp, Fcp, Vcp) indicating that tandem–seesaw was a more difficult stance to maintain in LAT direction. The seesaw stances (shoulder width and tandem) revealed larger amplitude, frequency and velocity of the CP-fluctuations in AP direction compared to the shoulder width stance. Since a direct comparison between postural stances was not the goal of this study, the remainder of the results section will focus on the interactions effect.

3.2. Postural sway

A main effect of Stroop was only found in the AP direction ($F_{3,21} = 5.58$, $P < 0.001$) and was related to a

Table 1
Changes in postural control for each postural stance following the addition of the Stroop task[a]

CP displacement	Direction	Shoulder width	Shoulder–seesaw	Tandem–seesaw
RMS amplitude	AP	N.S.	Decrease (29.57%)	N.S.
	LAT	N.S.	N.S.	N.S.
Mean frequency	AP	Increase (28.15%)	Increase (31.67%)	Increase (18.14%)
	LAT	N.S.	N.S.	Increase (19.42%)
RMS velocity	AP	N.S.	N.S.	N.S.
	LAT	N.S.	N.S.	Increase (25.35%)

[a] Percentage of change was calculated with respect to the word card task since no significant changes were found between the different Stroop tasks. N.S. = non-significant.

significant interaction ($F_{6,18} = 3.96$, $P < 0.05$), revealing that participants were only affected by the addition of a Stroop task when standing in the shoulder–seesaw stance. This change in postural sway was characterised by a *decrease* in amplitude independently of Stroop task difficulty (see Table 1 and Fig. 2a).

3.3. Postural frequency

A main effect of Stroop task was found in both directions (AP = ($F_{3,21} = 20.28$, $P < 0.001$); LAT = ($F_{3,21} = 20.94$, $P < 0.001$)). Only LAT balance revealed a significant interaction effect ($F_{6,18} = 2.75$, $P < 0.05$) indicating that the tandem–seesaw stance was more affected by the addition of a Stroop task than the other stances (see Table 1 and Fig. 3b). No interaction was found in AP direction, indicating that all stances were equally affected by Stroop task performance, independently of task difficulty.

3.4. Postural stability

A main effect of Stroop ($F_{3,21} = 13.19$, $P < 0.001$) and an interaction of Balance × Stroop ($F_{6,18} = 9.15$, $P < 0.001$) was found in the LAT direction only (see Table 1). The interaction revealed that only the tandem–seesaw stance produced significant changes when a Stroop task was added. This increase in velocity appeared independent of Stroop task difficulty (see Fig. 4b).

3.5. Stroop data

Because the mean number of uncorrected Stroop errors in all conditions never exceeded one, we only analysed the number of completed Stroop items. Fig. 5 presents the group means of the number of completed items for the various Stroop tasks. The only relevant finding was a large main effect of Stroop ($F_{2,22} = 355.56$, $P < 0.001$), with the slowest speed of performance on the CWC task and the fastest on the WC task.

4. Discussion

This study was conducted to investigate if and to what extent postural control in healthy young adults is vulnerable to cognitive task performance when participants are confronted with different support-surface configurations. It was predicted that dual-task interference would be substantial when there would be a necessity to shift towards poorly developed control strategies, but little or absent when the execution of a postural task would still be adequately subserved by a combination of well-developed, prestructured synergies. The global results of this study corroborate these predictions based on the novelty and difficulty of the postural task.

It is important to note that a systematic overestimation of the calculated CP-fluctuations (based on vertical

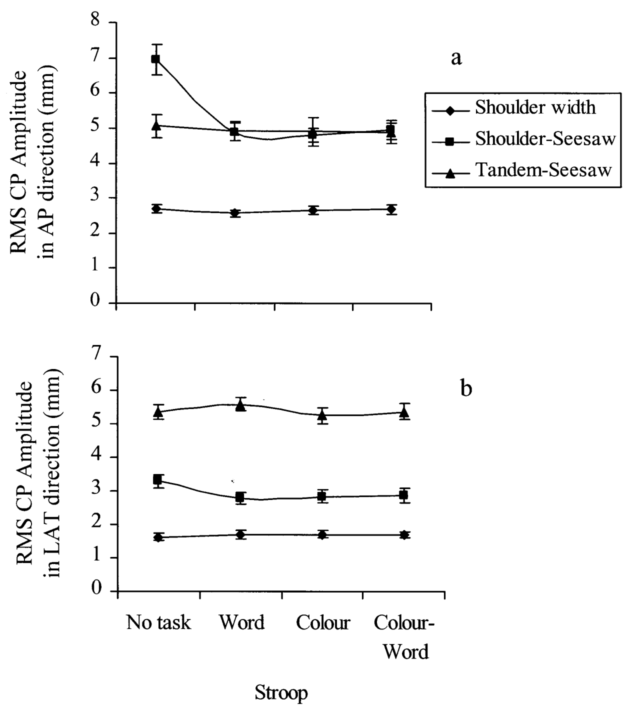

Fig. 2. RMS CP amplitude in AP (a) and in LAT directions (b) for all postural stances and Stroop conditions.

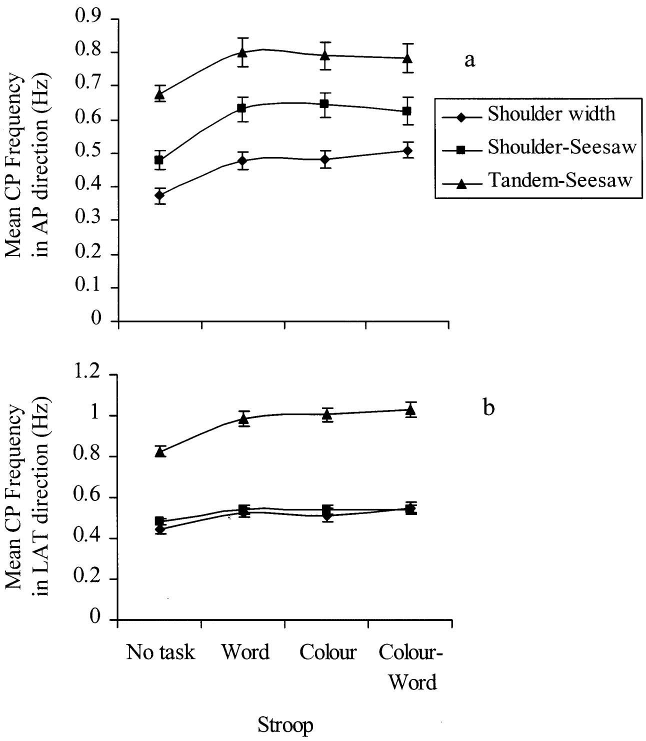

Fig. 3. Mean CP frequency in AP (a) and in LAT directions (b) for all postural stances and Stroop conditions.

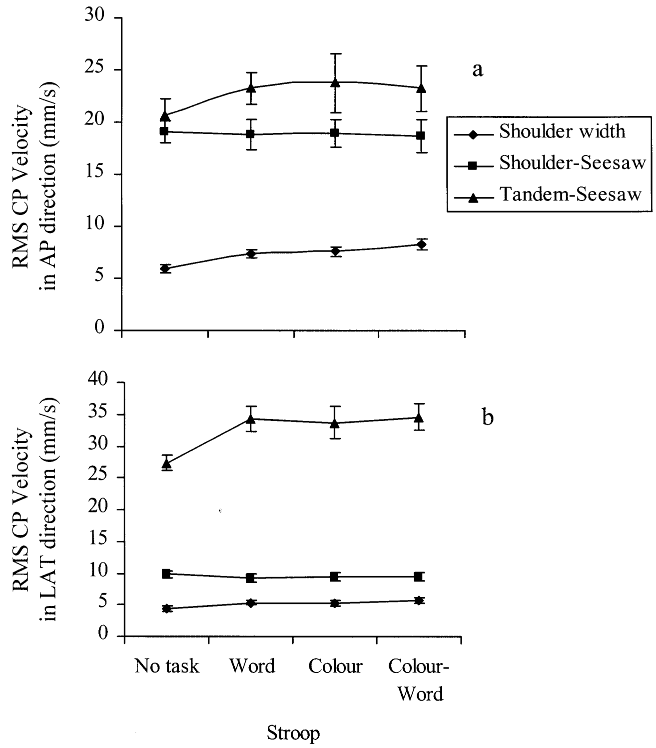

Fig. 4. RMS CP velocity in AP (a) and in LAT directions (b) for all postural stances and Stroop conditions.

ground reaction forces only) in the frontal plane may occur as a result of the added volume of the seesaws between the feet and the force platform. This may be particularly the case during tandem–seesaw stance which is characterised by relatively high expected lateral shear forces at the level of the platform. Hence, the absolute lateral *A*cp and *V*cp values for all tandem–seesaw conditions cannot directly be compared to the identical parameters in the other standing conditions. Nevertheless, the observed dual-task effect for lateral sway control during tandem–seesaw stance was entirely related to an increase in the mean frequency given the very stable *A*cp values for different Stroop tasks (see Figs. 2 and 3). Hence, the observed interaction effects for CP frequency and velocity in the frontal plane can safely be interpreted as a postural stability modification.

The changes found in the tandem–seesaw condition when the Stroop task was executed were most apparent in the LAT direction which corroborated our prediction based on the need of a major change in balance strategy. The results contrast those of Kerr et al. [19] who found changes in the cognitive task performance but not in the tandem stance control. These differences may be related to the fact that Kerr et al. [19] used CP measures that are insensitive to changes of frequency (mean absolute distance and standard deviation from the mean position, in addition to the absolute total maximum deviation) whereas this study shows that the influence of the cognitive task performance on postural control during tandem stance is a pure frequency effect. Our finding that the *A*cp was not modified can be regarded as a correct adaptation to the small lateral size of the support base when standing with the feet in a tandem position.

Following the addition of the cognitive task, a marked amplitude–frequency trade-off occurred for the shoulder–seesaw stance in the AP direction which left the CP velocity unchanged. When considering the stiffness model proposed by Winter et al. [30], such a trade-off may be interpreted as (indirect evidence of) an

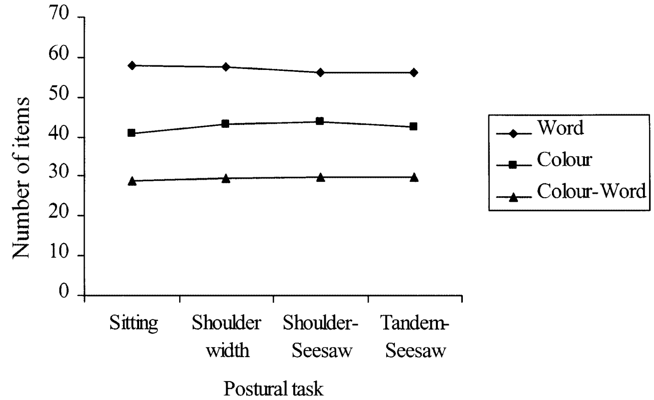

Fig. 5. Average number of items completed for all Stroop tasks for each postural stance.

increase in stiffness [31]. Similar results have been found in previous research when executing other types of cognitive tasks [23,21]. A trade-off between amplitude and frequency of the CP-fluctuations can be accounted for in terms of an adaptation of timing and gain of normally employed synergies to achieve a more critical stabilisation of posture. Such an adaptation probably facilitates the uptake of visual information from the Stroop cards.

We did not find any influence of the level of difficulty of the Stroop task on the degree of dual-task interference during any of the postural stances. This lack of discrimination between the different dual-task conditions can be attributed to the fact that the speed of the Stroop task performance (i.e. the number of completed items) was consistently lowest for the CWC task and highest for WC task (see Fig. 5). This reduction in speed of performance could be evidence of increased difficulty; in order to minimise errors in the execution of the task, speed had to be reduced [21]. However, because of this reduction in speed, the differences in task difficulty may have been neutralised, leaving the central processing demands unaltered. Therefore, we are unable to conclude if a higher level of difficulty of the cognitive task would produce larger dual-task interference. Nonetheless, our results clearly indicate that the difficulty and the novelty of the postural task do, in fact, cause varying ways of interference within a dual-task paradigm.

In trying to understand how the interaction between postural control and attention occurs, we must first of all determine if such interaction is related to a specific cognitive subsystem ('structural' interference) or if it is related to a more generalized attentional capacity [32]. The Stroop task used in this study necessitates the use of vision which may produce a structural interference since postural control is also influenced by this same sensory modality. The possibility of visual interference mechanisms as a partial explanation for the observed dual-task interference should be considered because, in comparison with normal upright standing, the importance of visual information in the control of posture is increased during tandem stance, especially with regard to lateral sway control. In particular, the possible influence of eye movement on the visual stabilisation of posture should be taken into account. Although some authors have reported a stabilising effect of voluntary eye saccades on postural control [33,34], others merely emphasised the absence of a destabilising effect as long as the frequency of the horizontal saccades is lower than 0.5 Hz and the amplitude smaller than 20–30° [35]. White et al. [36] reported that, in contrast with externally induced retinal image motion, similar image motion due to voluntary saccadic eye movements does not easily affect postural control even while standing on one foot. Since the three Stroop tasks always induced the same degree of interference (despite different speeds of performance), it is unlikely that the changes in postural sway found in this study would be mainly due to eye movements even for the tandem stance. Furthermore, the fact that focal vision (for object recognition, such as in the Stroop task) and ambient vision (for spatial orientation, such as in postural control) operate in parallel as independent processing modalities [27,37,38], suggests that structural interference through the visual system is less likely to occur than interference through competition for a more general attentional capacity.

In conclusion, the addition of a cognitive task provoked minimal changes when standing in a well learned position such as during shoulder-width stance, indicating that this posture may only require a minimal amount of attention. When the seesaws were added to this stance, the addition of the cognitive task resulted in an increased stiffness (indirectly shown by an increase in CP frequency and a decrease in CP amplitude) as an adaptation of normally employed synergies to achieve a more critical stabilisation of posture. Furthermore, when the postural stance difficulty and novelty were increased, by incorporating a tandem position on seesaws, the addition of the cognitive task resulted in a decreased postural stability in the frontal plane (increase in CP frequency and CP velocity). It is inferred from this study and from the literature that this destabilisation, which can be provoked even in healthy young adults, is probably best accounted for by a generalized capacity interference [39], which can be explained by the fact that tandem seesaw stance is least automatic, especially in the frontal plane. It is important to add that the integrity of the CNS may further determine the attentional demands of postural control since numerous research has shown greater dual-task interferences in elderly and pathological populations when compared to healthy individuals [6–10,20,22].

Acknowledgements

The authors would like to acknowledge the technical help of Bart Nienhius, biomedical engineer at St-Maartkliniek-Research, as well as all the participants for their time and motivation.

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