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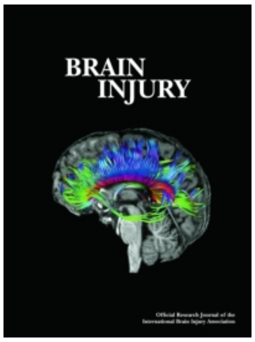

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Effects of spatial working memory in balance during dual tasking in traumatic brain injury and healthy controls

Ana Isabel Useros Olmo[a,b], Jose A. Periañez[c], David Martínez-Pernía[d,e], and Juan Carlos Miangolarra Page[f,g,h,i]

[a]Department of Physiotherapy, Motion in Brains Research Group, Instituto de Neurociencias y Ciencias del Movimiento, Centro Superior de Estudios Universitarios la Salle, Universidad Autónoma de Madrid, Spain; [b]Hospital Beata María Ana, Unidad de daño Cerebral, Madrid, Spain; [c]Department Experimental Psychology, Complutense University of Madrid, Madrid, Spain; [d]Center for Social and Cognitive Neuroscience (CSCN), School of Psychology, Universidad Adolfo Ibáñez, Universidad, Santiago, Chile; [e]Geroscience Center for Brain Health and Metabolism (GERO), Faculty of Medicine, University of Chile, Santiago, Chile; [f]Universidad de Medicina Física y Rehabilitación de la Universidad Rey Juan Carlos, Madrid, Spain; [g]Servicio de Medicina Física y Rehabilitación del Hospital Universitario de Fuenlabrada, Madrid, Spain; [h]Consejería de Salud, Comunidad de Madrid, Servicio Madrileño de Salud (SERMAS), Madrid, Spain; [i]de la Universidad Rey Juan Carlos, Madrid, Spain

ABSTRACT

Objectives: The aim of this research was to assess cognitive-motor interactions though dual tasks of working memory in patients with traumatic brain injury (TBI) and control subjects. **Methods**: Twenty patients with chronic TBI with good functional level and 19 matched healthy controls performed dual working memory tasks (1-back numeric and 1-back spatial (S)) while sitting, standing, and walking. The center of pressure (COP) displacement amplitude, cadence, and error percentage (PER) were recorded as dependent variables. **Results**: The results revealed main effects of Group (TBI, controls) ($p = .011$) and Task factors (Single, Dual Standing 1-back, Dual Standing 1-back (S); $p = .0001$) for the COP. Patients showed greater displacement than controls ($p = .011$), and an analysis of the Task factor showed a minor displacement for the dual 1-back (S) task compared with the 1-back and single task ($p = .002$ and $p = .001$, respectively). **Conclusions**: Postural control during both standing and walking improved during performance of the spatial working memory task. In the dual task, both patients and controls showed a postural prioritization as an adaptive response to the increase in cognitive demand.

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Brain injury; motor control; working memory; dual task; limited resources model

Introduction

In daily life, balance or, more broadly, postural control acts most of the time in multitasking contexts. Currently, thanks to dual task paradigms, we know of the participation of different cognitive processes in postural control (1–6). In general, these processes optimize motor function and help to adequately respond to the changing demands of the environment. Disruptions in these processes can be reflected in motor alterations, for example, in gait disorders (7–13).The nature of this relationship and its multiple interactions is currently an emerging field of research (14).

Traumatic brain injury (TBI) is frequently associated with a loss of movements that were previously automatic, such as standing or walking, which implies an increase in the cognitive processing demands for the conscious control of movement and diminishes the ability of the individual to simultaneously perform two tasks. The causes of these difficulties include the loss of motor automatism after brain injury. Thus, postural control depends on voluntary control, requiring greater attention to the posture and therefore diminishing the capacity of the affected individual to perform two tasks at the same time (15,16). Other causes that explain the difficulty experienced by people with TBI in performing dual tasks are attentional problems and diffuse axonal injuries, which may decrease the speed of processing and the ability to simultaneously perform two tasks (17–19).

In the last 20 years, some studies on dual tasks in individuals with TBI have been conducted (15,16,20–25) allowing the study of the motor alterations of patients through a new paradigm (26).

However, the interpretation of the results from these studies raises a series of theoretical and methodological difficulties. In general, it is accepted that the cognitive system has a limited processing capacity (27–31). When tasks share similar resources (structural or processing), i.e., when a posture is maintained and a different spatial task is performed at the same time, someg studies have shown that the spatial task may interfere postural control (2,32), while others have shown positive interaction effects improving postural control (33–35). In these cases, theories such as limited resources show clear difficulties explaining these improvements in postural control, so the appearance of new data such as those mentioned has promoted the emergence of new alternative explanations. There are other limitations in the existing literature. On one hand, few studies have investigated the effects of motor activity on cognitive performance (27–31,36–41). On the other hand, the lack of fixation points in visual tasks (37) or the use of vocal responses that would enhance postural destabilization

CONTACT Ana Isabel Useros Olmo anaiuseros@gmail.com Department of Physiotherapy, Motion in Brains Research Group, Instituto de Neurociencias y Ciencias del Movimiento, Centro Superior de Estudios Universitarios la Salle, Universidad Autónoma de Madrid, Madrid, Spain

(27,29,36,37,39–41) could question the validity of some of the existing data.

The main aim of the present study was to describe differences in motor behavior during dual tasks requiring working memory processes (1-back numeric and 1-back spatial (S)) in patients with TBI *versus* healthy controls. Until now, few studies on brain injury have described patients' motor performance during dual tasks of working memory being their contradictory findings.

Methods

Participants

The sample of individuals with TBI participating in the present study was selected according to inclusion and exclusion criteria, as described below, from the total population of patients being attended in the Brain Injury Unit at the time of running the present investigation. The inclusion criteria were (a) to have a medical and neuroimaging diagnosis of TBI, (b) a period greater than 18 months since the TBI occurred, (c) age between 18 and 65 years, (d) independent standing, and (e) ability to walk without technical or manual aids. The exclusion criteria were (a) score on the Berg scale <45; (b) score in the Mini Cognitive Examination (MCE) ≤27; (c) aphasia; (d) resting or intentional tremor; (e) heminegligence; (f) visual problems not corrected with lenses; and (g) consumption of antidepressant or antiepileptic drugs capable of influencing cognitive performance.

Healthy matched individuals were selected among patient relatives and the Brain Injury Unit personnel. They were trauma-free and matched for age, sex, height, weight, education, and socioeconomic status. No subjects had histories of neurological disease, psychiatric illness, head injury, stroke, nor learning disabilities. All participants had normal or corrected-to-normal vision.

The procedures used to carry out this study followed the ethical principles of medical research in humans as set out in the Declaration of Helsinki adopted at the 18th Assembly of the World Medical Association (WMA, Helsinki, Finland, June 1964) and approved by the Ethical Assistance Committee of the Hospital Beata María Ana de Madrid. All subjects were informed of the objectives and characteristics of the study and gave their written consent to participate. The experiment was carried out in the facilities of the Brain Injury Unit of the Hospital Beata María Ana de Madrid in two well-differentiated phases: the initial evaluation phase and the experimental phase.

Initial evaluation

The application of inclusion and exclusion criteria yielded a sample of 20 TBI participants (17 males, 3 females, mean age = 36.15 years, SD ± 12.51; mean education level = 12.9 years, SD ± 3.1; mean height = 171.4 cm, SD ± 8.3) and 19 healthy participants (17 males, 2 females, mean age = 38.2 years, SD ± 13.4; mean education level = 13.7 years, SD ± 3; mean height = 172.9 cm, SD ± 9.8). See a detailed description of the two samples in Table 1.

Table 1. Demographic characteristics of the initial sample.

Characteristics	TBI n = 20	Controls n = 19	p
Age	36.15 ± 12.51	38.2 ± 13.4	0.63
Sex (n)			
Male	17	17	0.77
Female	3	2	
Education level (years)	12.9 ± 3.1	13.7 ± 3	0.42
Height (cm)	171.4 ± 8.3	172.9 ± 9.8	0.61
Glasgow	5.8 ± 3.4	-	-
Time of injury (months)	35.5 ± 20.2	-	-
Mini-Cognitive Exam (MCE)	32.8 ± 1.5	-	-
Barthel Index	100	-	-

Note: The values are presented as the mean ± standard deviation.

The initial evaluation phase lasted approximately 45 minutes, and began with an interview, in which general information about personal and clinical data was collected. Then, a neuropsychological evaluation was carried out that used the Trail Making Test (TMT) (42), Stroop Test (43), Digit Symbol of the WAIS-III (44), Digits Forward and Digits Backwards of the WAIS-III (44), and a computerized Finger Tapping task (45–47).

Experimental phase

The second phase, or experimental phase, occurred during a single session lasting approximately 45 minutes, which was held 5 to 7 days after the initial evaluation. We implemented single and dual tasks in different postural conditions to conceive the motor tasks as a graded manipulation of postural control demands. Single tasks were performed under standing and walking conditions. Dual tasks were performed under sitting, standing, and walking conditions while the participant performed a cognitive task (a numerical working memory task (1-back numeric) and a spatial working memory task (1-back (S)). The instructions given to participants in the dual task conditions did not prioritize the motor or cognitive task.

Cognitive tasks were designed using *Presentation*® software (http://www.neurobs.com) for the presentation of stimuli and recording responses. Body position during single and dual tasks was controlled by the same postural criteria for all subjects. The participants were placed one meter away from the screen, ensuring that the height of the screen would be located at eye level for all of the participants. The total duration of each task was 120 seconds. Before performing the task, the subjects received the instructions orally and in writing. These instructions emphasized the importance of responding as fast as possible keeping the eyes on the TV screen. The order in which the tasks were performed was randomized to control for a potential asymmetrical modulatory effect of learning and fatigue on differences between tasks.

The following provide the characteristics of the cognitive tasks:

Numerical working memory task (1-back numeric): In this 1-back task, subjects were instructed to press the left mouse button if the stimulus that appeared in the center of the screen (a number from 1 to 9) was equal to the stimulus they had seen in the immediately preceding trial. (Figure 1a)

Spatial working memory task (1-back (S)): This task consisted of pressing the left mouse button if the circle that appeared on the screen coincided in position with the circle

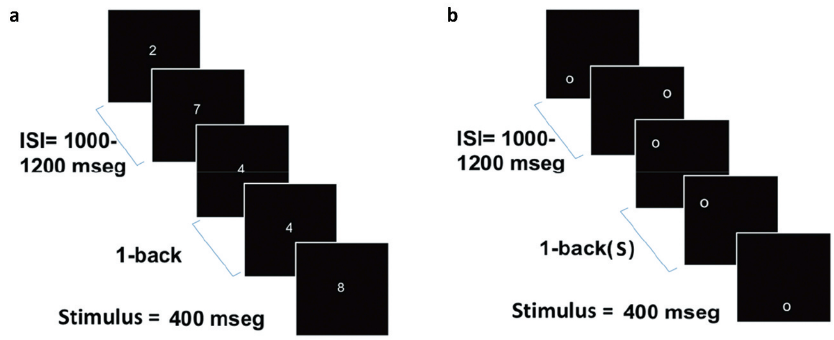

Figure 1. Numerical working memory task (a) and spatial working memory task (b). In both conditions the stimulus lasted 400 ms and the interval between stimuli was randomized between 1000 and 1200 ms.

presented in the immediately preceding trial. A total of 9 possible positions were established (coinciding with the number of fixed items in the numerical working memory task). The nine possible positions resulted from the combination of three horizontal positions (left, center, and right) and three vertical positions (top, center, and bottom). (Figure 1b).

During the standing task, the instruction given to the participants consisted on standing motionless, arms relaxed along the body and facing forward to a fixed point on the TV screen. The subjects remained standing on a portable square balancing platform measuring 620 × 610 x 60 mm (BT4, Hurlabs Oy, Tempere, Finland, HurLabs Co, www.hurlabs.com). During the test, a continuous posturographic record was made over a period of 120 seconds from the parameters provided by the platform whose sampling rate was 50 Hz at the x and y coordinates of the COP every millisecond. The position of the feet was controlled for all subjects under both experimental conditions (single and dual tasks) by maintaining a 5 cm distance between heels and a separation angle of 30 degrees.

During the walking task, the participants were instructed to walk on a treadmill (Gait Trainer 2, Biodex) without manual support facing forward toward a fixed point on the TV screen. The researchers selected a constant speed of 3 km/h on the treadmill, which is the average walking speed of healthy subjects (48). Before starting the task, the subjects walked for a few seconds on the treadmill until they reached the selected speed. Once this speed was reached, the task was performed for 120 seconds.

Data analysis

The performance of participants in the motor tasks on the force platform was measured by analyzing the amplitude of the angular displacement of the pressure center (COP) on the x-y axis (mm) and the speed of displacement of the COP (mm/s). With the aim of ensuring that the displacements of the COP were independent from the stature of the subjects, the linear displacements were transformed into a value equivalent to the angular oscillation of the body around the support base. We used the approach proposed by Baydal-Bertomeu et al. (49), where the equivalent angle (α) of body oscillation is calculated based on the known maximum displacement of the COP and the approximate height of the center of gravity (obtained from the height of the subject and anthropometric tables).

The treadmill software (Gait Trainer 2, Biodex) was used to obtain the results from the walking test; the software is specifically designed for training and evaluating gait in patients with neurological problems (50,51). The treadmill software offers the possibility of specifically designing different running tests that vary the parameters of time and speed. Once the walking task was complete, a results sheet was generated with the cadence parameters obtained during the task. The performance on cognitive tasks under both single and dual conditions was measured by analyzing the percentage of errors (PER).

Statistical analysis

The Kolmogorov-Smirnov test was used to determine if the descriptive variables showed a normal distribution. Those variables that did not show a normal distribution were compared using non-parametric hypothesis testing (Mann-Whitney U), while the variables with a normal distribution were compared using a parametric test (Student's t test). To analyze the clinical motor characteristics of the sample, Student's t test was used for continuous variables and the Chi^2 test was used for categorical variables. For the comparison of baseline cognitive performance between patients and controls, 2 × 2 mixed ANOVAs were applied to determine group effects (TBI vs controls) and working memory (1-back numeric, 1-back (S)). Two mixed 2 × 3 ANOVAs including Group (TBI, controls) and Task factors (single, dual standing 1-back, and dual standing 1-back (S) tasks) were performed to evaluate changes in the angular displacements of the COP and cadence. For the evaluation of the cognitive performance, several mixed ANOVAs (2x3x2) were used on the PER, including the factors of Group (TBI, controls), Task (dual task sitting, dual task standing, dual task walking) and Working Memory (1-back, 1-back (S)) and associated interactions. The probability of false positive results was controlled by post-hoc comparisons using the Bonferroni correction for multiple comparisons to identify specific differences between groups and tasks. All analyses were conducted using SPSS (version 20, SPSS Inc., Chicago, Illinois).

Results

Clinical features

In the motor tests, Student's t tests showed significant differences between groups for the Berg scale score (p = .003). However, these differences were not found in postural control during the single standing task on the platform, displacement of the COP (p = .09), or the cadence during walking (p = .26) (Table 2).

Student's t-tests showed significant differences between groups (p < .05) in the neuropsychological Stroop Test (word) (p = .005), Trail Making Test (A and B) (p = .001; p = .001), Digit Symbol (p = .009) and finger tapping tests (p = .013). The patients showed worse baseline scores on the speed processing tests compared to the controls; however, these differences were not found in the attention or memory tests (Stroop C and Stroop PC, Trail Making Test (B-A), Forward and Backward digits) (Table 3).

The mixed ANOVA (2x2) for the PER included the factors Group (TBI, controls) and Memory (1-back and 1-back (S)). The analysis showed main effects of Group, where the patients showed a higher PER than the controls (F (1,37) = 4; p = .04). However, they did not show main effects for the Task factor (F < 1; p = .295) or interaction between the factors (F < 1; p = .09) (Table 4).

Motor performance when standing: single task vs dual task

The mixed ANOVA (2x3) for the angular displacements of the COP on the balancing platform that included the factors Group (TBI, controls) and Task (single, dual standing 1-back, dual standing 1-back (S)) revealed main effects for Group (F (1,37) = 7.165; p = .011; Power = 0.74), and for the Task factor (F (2,74) = 10.6; p = .0001; Power = 0.98). Post-hoc analysis for the Group factor showed greater displacement of the COP in patients than in controls. The Post-hoc analysis of the Task factor showed significant differences between the dual tasks 1-back (S) and 1-back (p = .002; mean COP 2.3 ± 0,9 and 2.6 ± 0,11, respectively) and between the dual task 1-back (S) and the single task (p = .001; mean COP 2.3 ± 0,9 and 2,7 ± 0,98, respectively), with no significant differences between the tasks 1-back and single (p = 1). However, no interaction was found between the factors (F < 1; Power = 0.13) (Figure 2).

Table 2. Motor characteristics of the initial sample.

Motor characteristics	TBI n = 20	Controls n = 19	p
Balance test			
Berg scale	54.80 ± 1.43 (51–56)	55.95 ± 0.22 (55–56)	0.003
Simple motor tasks			
COP displacement amplitude (º)	2.92 ± 0.67 (2,64–3,2)	2.58 ± 0.54 (2,3–2,8)	0.09
Cadence (steps per minute)	91 ± 9.56 (87,5–94,8)	94 ± 6 (90,4–97,9)	0.263

NOTE. The values are presented as the mean ± standard deviation (range)

Table 3. Neuropsychological characteristics of the initial sample.

Characteristics	TBI n = 20	Controls n = 19	p
Stroop Word	88.8 ± 15.6	104.8 ± 17.5	0.005[a]
Stroop Color	67.6 ± 13.6	73.5 ± 12.4	0.17
Stroop Word-Color	43.7 ± 12.2	46.9 ± 11.2	0.4
Trail Making Test A	44.8 ± 14.1	28.8 ± 8.1	0.0001[b]
Trail Making Test B	88.6 ± 29.6	61.3 ± 29.6	0.001[b]
Trail Making Test B-A	43.8 ± 24.4	32.5 ± 15.8	0.09
Digit Symbol	61.9 ± 18.9	79.8 ± 21.7	0.009
Forward digits	8.6 ± 1.9	9.1 ± 2.5	0.53
Backward digits	6 ± 1.9	6.4 ± 2.2	0.53
Finger tapping	219 ± 47.1	189.1 ± 17.2	0.015[b]

Table 4. Characteristics of cognitive task PER of the initial sample.

Single cognitive tasks	TBI n = 20	Controls n = 19
1-back PER	0.73 ± 1.22	0.51 ± 0.85
1-back (S) PER	1.54 ± 2.26	0.32 ± 0.69

NOTE. The values are presented as the mean ± standard deviation (PER = percentage of errors, 1-back = numerical working memory task, 1-back (S) = spatial working memory task).

Motor performance while walking: single task vs dual task

The mixed ANOVA (2x3) for the cadence recorded on the treadmill that included the factors Group (TBI, controls) and Task (single, dual walking 1-back, dual walking 1-back (S)) revealed main effects for the Task factor (F (1,50) = 3.52; p = .034; Power = 0.64). Post-hoc analysis revealed marginally significant differences (p = .08) between the dual 1-back (S) task that increased the cadence more than the single task (Figure 3), but not between the 1-back and 1-back (S) tasks (p = .455) or between the single and 1-back tasks (p = .424). No significant effects were found for the Group factor (F < 1; Power = 0.06) or interaction between factors (F < 1; p = .14; Power = 0.39).

Cognitive performance: sitting, standing, and walking dual task

The mixed ANOVA (2x3x2) for the percentage of errors that included the factors Group (TBI, controls), Task (dual task sitting, dual task standing, dual task walking), and Memory (1-back, 1-back (S)) revealed main effects for Task (F (2,74) = 9.328; p = .0001). Post hoc analysis revealed significant differences between the dual task walking and the dual task sitting, and between the dual task walking and dual task standing (p < .03), with the percentage of errors in the dual tasks (walking and standing) being higher than in the dual task sitting. However, no differences were found between the dual standing task and the dual task sitting (p = .235). No significant effect was found on the Group factor (F < 2,3; Power = 0.306), the Memory factor (F < 1.5; Power = 0.22) or interactions between the factors (F < 1; Powers < 0.13) (Figure 4).

Discussion

Most current theories on motor control postulate a close coordination between motor and cognitive processes for the elaboration of effective strategies of adaptation to the environment, which produces a paradigm shift in clinical intervention and raises new working hypotheses. In the present study, the main aim was to assess the interaction effect between working memory tasks (1-back numeric and 1-back spatial tasks) on the motor control of patients with TBI and control subjects. According to the model of limited resources, it would be expected that motor performance would decrease in the dual tasks of spatial memory 1-back (S). This research shows for the first time that dual spatial working memory tasks

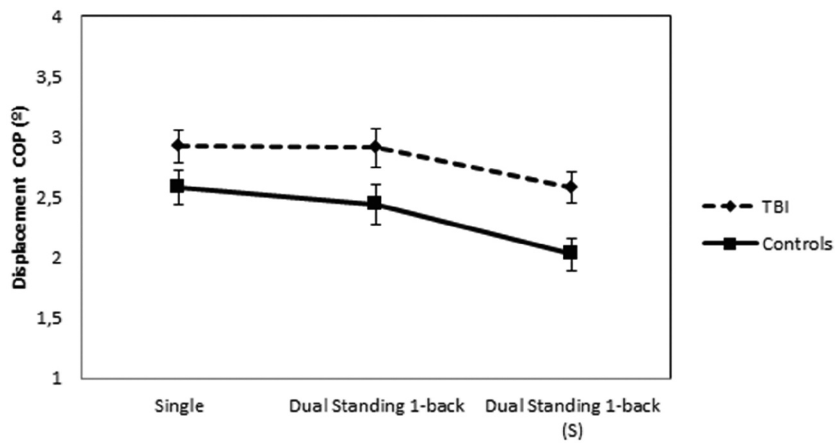

Figure 2. Means and standard errors of the displacements of COP in the x-y axis between TBI and controls in single and dual tasks (Single = single task, Dual standing 1-back = standing dual memory task, Dual standing 1-back (S) = standing dual spatial memory task).

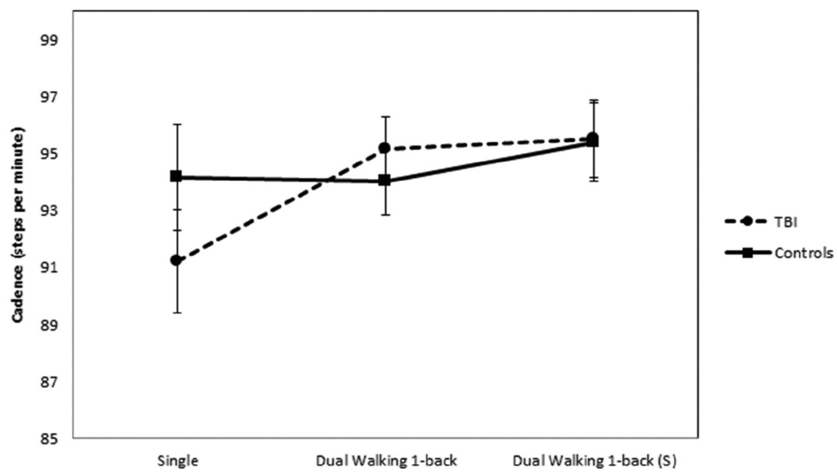

Figure 3. Means and standard errors of the cadence between TBI and controls in single and dual tasks (Single = single task, Dual Walking 1-back = dual memory task, Dual Walking 1-back (S) = dual spatial memory task).

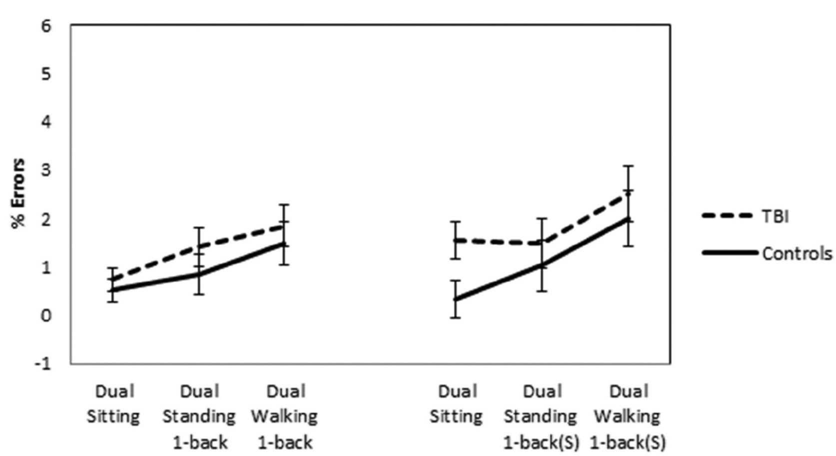

Figure 4. Means and standard errors of the % errors in TBI and controls in dual tasks conditions (a numerical working memory task (1-back numeric) and a spatial working memory task (1-back (S)) under sitting, standing, and walking conditions).

improve stability while standing, and increase cadence in both healthy subjects and patients with TBI.

At baseline, the patients group showed a global slowdown and specific deficits in working memory as compared to controls. These results, together with neuropsychological testing, confirm information processing slowness in patients with TBI (Table 3). At the motor level, patients with TBI showed postural control similar to controls while standing and walking under single task conditions. However, differences in the Berg scale reflected worse balance in patients with respect to controls, although the magnitude of such differences was small (1 point on average) (Table 2). These results are consistent with preceding literature showing that disorders of balance and coordination are present in most patients with TBI (52,53) and persist for years even in mild TBI (54).

A novel finding of the present study was that during the dual tasks of standing and walking and spatial memory there were positive interaction effects on motor performance. In the dual task of standing and spatial memory 1-back (S) vs single task (standing) postural control improved in both patients and controls (Figure 2). The analysis showed a decrease in the amplitude of the COP in the task of spatial memory vs the task of numerical memory and the single task (standing) in both patients and controls. In brain injury, there are no studies that have used dual tasks of standing and spatial working memory, so it is not possible to compare these results. The results of studies that have investigated the effects of different non-spatial working memory tasks on standing vary between a decrease in postural control (55), absence of changes (37,52) or improvement of postural control (30). Similarly, in the dual walking tasks, the spatial memory task increased the cadence. Like the present study, in the study by Dennis et al. (28), the authors found an increase in walking speed during the spatial memory task but not during the non-spatial memory task. According to the previous literature in healthy subjects, other authors who studied the effect of different working memory tasks also found positive interaction effects in postural control, especially in young adults (56–58). These positive interactions in postural control during dual tasks have been attributed by some authors to an increase in the level of arousal (59,60). It should be noticed that the term arousal (or the "alerting network", as defined in classical models of attentional brain networks (61) may represent a neuroanatomical and cognitive set of attentional resources that are relatively independent, although interrelated to, of more task specific attentional resources (i.e., orienting or executive attentional networks). According to some authors, memory tasks consume more specific attentional resources, particularly in the case of novel or complex situations, which may indirectly modulate the level of arousal (56,57). Complementarily, it is known that novel situations may recruit hippocampal involvement, which in turn may activate different subcortical brain regions devoted to automatic movement control and learning mechanisms (20,58–60,62,63). In this vein, dual tasks represented a new task for both patients and controls that, added to the cognitive demands of the memory tasks, could increase arousal in order to activate motor learning mechanisms (Maylor, Allison, & Wing, 2001) (64). The presence of a positive interaction while standing and walking in the dual spatial memory task and not in the numerical memory task, showed in the present study, will be compatible with and increase in arousal as suggested by the limited resources model.

In the present study, three motor tasks with different levels of difficulty were used, expecting to find a decrease in cognitive performance in the more complex tasks (walking and standing) (62). To verify whether the prioritization model was met, a pre-set speed was used as the autonomous running speed. According to this model, a prioritization of motor performance vs cognitive performance would be expected, especially when the level of cognitive demand increases. Based on this interpretation, prioritization may constitute a compensatory strategy that is strategically adopted by individuals. The results of this study confirmed this hypothesis by showing a decrease in cognitive performance in the dual walking tasks but not in the dual standing tasks in both patients and controls. In the dual walking tasks (1-back and 1-back (S)), the PER increased with respect to the dual standing tasks and the dual sitting task (Figure 3). These results are consistent with previous literature on brain injury that have found that walking is a more demanding task than standing (30,31) and that the degree of complexity of the motor task influences the degree of cognitive-motor interference during the dual task (27,36,55,63).

Traditionally, motor rehabilitation aims to treat motor and sensory components, and learning is considered a procedure associated with frequent repetitions of task-specific exercises (65–67). Dual-task training has recently been proposed to be more effective in motor learning than in simple task training (68,69). Recent literature shows that training participants in a cognitive task (attention, cognitive flexibility, and autobiographical memory) while they are performing a motor task improves motor performance (70,71). The results from the present study could be considered preliminary evidence supporting the hypothesis that performing a 1-back spatial working memory task while performing a physical task improves motor behavior. Particulary, motor rehabilitation programs based on the proposed dual-task represent a promising avenue in improving TBI patient motricity.

Several studies have shown that dual-task training to rehabilitate neurological disorders improves cognitive domains (cognitive flexibility, speed processing, executive function) (72–74). Likewise, different cognitive rehabilitation programs have shown that working memory is a cognitive domain that improves with training (75–77); and furthermore, that such improvement is transferred to other cognitive domains that were not the target of training (75–78) such as vigilance, sustained attention, spatial memory working, inhibition of unwanted responses, and reasoning (79–81). Given the results of this experimental study and the support it receives from the literature, further research into rehabilitation programs based on this dual-task proposal are necessary to provide greater fidelity into effects on TBI patient motor and cognitive skill improvement.

Finally, it is worth mentioning some methodological limitations of this work. i) The results should not be extrapolated to patients in acute and subacute stages of TBI (since the present sample was in the chronic stage post-injury), or with a lower level of motor functionality. ii) The small sample size might have limited our ability to detect interaction effects on the COP, as well as other potential effects that were marginal or not significant in the established comparisons. iii) Although this study shows a greater cadence in the dual walking 1-back (S) task in both groups, new studies that incorporate spatiotemporal variables of gait are necessary to conclusively determine whether these changes indicate an increase or a decrease in the stability of participants.

The limitations mentioned above may be addressed in future studies, especially with wider samples. Further research may also expand upon the working memory tasks used in this study with e.g., stepwise difficulty levels to investigate their effects on motor behavior and cognitive performance. And finally, future research would ideally avail of more precise technological instruments (e.g., 3D motion capture, 2D kinematics, GAITRite electronic walkway) for gauging spatiotemporal gait variables (e.g., stride width, stride length, stride time, variability in step length).

Conclusion

In summary, the results of the present study showed that patients with TBI exhibited an improvement in postural control when they performed a dual task involving spatial working memory, which could reflect a prioritization model based on an increase in arousal under the assumption that available resources, both structural and cognitive, are limited.

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ORCID

David Martínez-Pernía http://orcid.org/0000-0003-2830-7920

Declaration of interest

We do not have any conflict of interest.

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