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Patterns of cognitive-motor interference in patients with post-stroke cognitive impairment

Vzorce kognitivně-motorické interference u pacientů s poruchou kognitivních funkcí po cévní mozkové příhodě

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Abstract

Aim: The study aimed to investigate the patterns of cognitive-motor interference in patients with post-stroke cognitive impairment (PSCI), compared to age-matched control groups with probable mild cognitive impairment (pMCI) and normal cognitive function (individuals with cognitive abilities intact; ICA). *Methods:* We recruited 28 patients (mean age ± SD: 63.4 ± 12.1 years) with PSCI for a cross-sectional study. The age-matched control group included 50 individuals, divided based on Montreal Cognitive Assessment (MoCA) scores into a pMCI (67 ± 10.3 years; MoCA ≤ 25) and ICA group (62.2 ± 8.5 years; MoCA ≥ 26). We used the usual walking speed to assess motor performance and the visual-verbal Stroop test to evaluate cognitive performance under different prioritisation conditions. The relative dual-task effect (DTE %) was calculated for each task to identify patterns of dual-task interference. *Results:* The DTE evaluation confirmed a decline in walking speed and an increase in performance on the Stroop test, regardless of prioritisation, in all tested groups. The groups demonstrated significant variability in DTE for walking speed with cognitive prioritisation (P = 0.0145). Cognitive-related motor interference (N = 17 across all groups) and cognitive priority trade-offs (N = 6 across all groups) were the most common patterns in gait prioritisation. Cognitive prioritisation led to greater differences in interference patterns, especially in the pMCI and ICA groups. The pMCI group showed an increased preference for cognitive facilitation (N = 8), compared to the ICA group, which displayed more cases of no dual-task interference (N = 11). *Conclusion:* The choice of cognitive prioritisation influenced the patterns of interference during dual-task performance among PSCI, pMCI, and ICA groups. Our study supports the use of dual-task paradigms with cognitive prioritisation as a tool to distinguish the progression between different levels of cognitive impairment.

Souhrn

Úvod: Cílem studie bylo porovnat vzorce kognitivně-motorické interference mezi pacienty s kognitivní poruchou po CMP (post-stroke cognitive impairment; PSCI), věkově odpovídajícími jedinci s pravděpodobnou mírnou kognitivní poruchou (probable mild cognitive impairment; pMCI) a osobami s intaktními kognitivními funkcemi (individuals with cognitive abilities intact; ICA). *Metody:* Do průřezové studie bylo zařazeno 28 pacientů s PSCI (průměrný věk ± SD 63,4 ± 12,1 roku). Kontrolní soubor tvořilo 50 věkově odpovídajících osob rozdělených podle výsledku Montreal Cognitive Assessment (MoCA) do skupiny pMCI (67,0 ± 10,3 roku; MoCA ≤ 25) a skupiny s ICA (62,2 ± 8,5 roku; MoCA ≥ 26). Hodnocena byla obvyklá rychlost chůze k posouzení motorických schopností a výkon ve vizuálně-verbálním Stroopově testu za různých podmínek prioritizace úloh k vyhodnocení kognitivních schopností. K identifikaci vzorců kognitivně-motorické interference byl pro obě úlohy vypočten relativní efekt dvojího úkolu (dual-task effect; DTE %). *Výsledky:* Ve všech skupinách došlo při plnění dvojího úkolu k poklesu rychlosti chůze a současně ke zlepšení výkonu ve Stroopově testu bez ohledu na podmínky prioritizace. Statisticky významné rozdíly mezi skupinami byly zjištěny v DTE rychlosti chůze při kognitivní prioritizaci (p = 0,0145). Při prioritizaci chůze převažovala kognitivně podmíněná motorická interference (n = 17 ve všech skupinách) a kompromisy v kognitivních prioritách (n = 6 ve všech skupinách), zatímco při kognitivní prioritizaci byla patrná vyšší variabilita vzorců interference, zejména ve skupinách pMCI a ICA. Ve skupině pMCI častěji převažovala kognitivní facilitace (n = 8), zatímco ve skupině ICA absence interference při dvojím úkolu (n = 11). *Závěr:* Kognitivní prioritizace ovlivnila vzorce kognitivně-motorické interference u skupin PSCI, pMCI a ICA. Naše studie podporuje využití paradigmat dvojího úkolu s kognitivní prioritizací jako nástroje pro diferenciaci stupně kognitivního postižení.

Key words

stroke – cognition – dual task – gait – interference

Klíčová slova

cévní mozková příhoda – kognice – dvojí úkol – chůze – interference

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Introduction

Stroke remains a leading cause of disability worldwide [1]. The development of prevention strategies, effective care in stroke units, and timely reperfusion therapy has contributed to global improvements in stroke treatment outcomes. However, post-stroke cognitive impairment (PSCI) still remains one of the main factors influencing poor long-term prognosis [2]. PSCI is a broad term that encompasses the entire spectrum from mild cognitive impairment to dementia and includes cases with purely vascular pathology or mixed pathology [3]. These deficits result in increased healthcare costs due to frequent hospitalizations, extended rehabilitation, and long-term care [4]. Therefore, there is a pressing need for timely intervention and optimal prevention of PSCI [5].

Community mobility requires the ability to adapt to external environmental factors that increase the difficulty of walking, such as obstacle avoidance and time-critical tasks like crossing the street with a traffic signal [6]. PSCI can reduce the automaticity in attention allocation during walking, which may consequently limit mobility in community-dwelling stroke survivors [7]. This phenomenon is known as cognitive-motor interference (CMI), where performing two different tasks simultaneously (e.g., walking and a cognitive task) results in deterioration in one or both task performances [8].

Cognitive-motor interference involves shared neural networks between motor and cognitive functions. Cerebral imaging evidence shows functional and structural links between motor control and cognition, such as prefrontal and temporal brain areas activated during movement (e.g., bilateral superior frontal gyrus and inferior parietal lobule, right middle frontal gyrus and middle occipital gyrus, as well as left inferior frontal gyrus, presupplementary motor area, and inferior temporal gyrus) [9,10]. A vascular deficit in any of these structures can cause changes in cognitive and motor performance, manifesting as reduced automaticity during walking [11]. In PSCI, this may manifest during dual-task walking, characterized by altered prioritization of postural control and increased gait variability. Consequently, this raises the risk of falls associated with PSCI [12].

Concurrent performance of a cognitive and motor task can lead to various distinct patterns of cognitive-motor interference. The pattern of CMI depends on several factors, including the types of cognitive tasks, difficulty levels, instructions about prioritization, and the characteristics of the individual performing the task (e.g., cognitive and motor abilities, fear of falling, distractibility) [13]. The pattern of CMI has not yet been examined in relation to PSCI and the occurrence of probable mild cognitive impairment (pMCI) in prodromal stages. Dual-task-related changes in gait are considered a sensitive marker of the adverse effects of cognitive impairment on the highest levels of gait control [14]. Building on this evidence, the aim of this study was to investigate cognitive-motor interference in patients with PSCI compared to age-matched control groups with pMCI and intact cognitive abilities (ICA).

Materials and methods

Study design and participants

28 PSCI patients were recruited from the University Hospital in Pilsen after being discharged home from acute care or inpatient rehabilitation facilities. Inclusion criteria for the experimental group were as follows: hospital admission for ischemic stroke with symptom duration of at least 24 h and radiological confirmation (CT and/or MRI, as indicated); lesions located in a cerebral hemisphere or supratentorial cerebral lesions; diagnosis of PSCI and no dementia confirmed through neuropsychological assessment; cognitive function evaluation: Montreal Cognitive Assessment (MoCA) ≤ 25; Mini-Mental State Examination (MMSE) ≤ 24; Clock Drawing Test (CDT) ≤ 3; modified Rankin Scale ≤ 2; an ability to walk continuously for 14 m without assistance to advance the involved lower limb (assistive devices and bracing not permitted); and an ability to follow instructions and communicate verbally. The time since stroke onset was not considered an eligibility criterion for study participation. The study cohort comprised individuals who underwent dual-task assessment during the subacute (1–6 months post-stroke) and chronic stages (> 6 months post-stroke) following stroke onset. The mean time since stroke onset was 4.0 months (range: 1.0–24.0 months).

The age-matched control group consisted of 50 subjects, divided into two groups based on their MoCA scores: a group with pMCI (MoCA ≤ 25) and ICA (MoCA ≥ 26). As the MoCA is a screening measure, the resulting group allocation reflects a research-based operationalization of cognitive status and should not be considered equivalent to a formal clinical or neuropsychological diagnosis. [15]. The selection process was conducted at the Faculty of Health Care Studies, University of West Bohemia, in Pilsen, Czech Republic. The inclusion criteria for the control group included being aged 45 years or older, being able to walk unaided without the use of mobility aids, and being capable of understanding and following instructions during testing [16]. Participants were excluded if they had musculoskeletal impairments affecting posture or gait (e.g., osteoarthritis), uncontrolled hearing or visual impairments, pre-existing or coexisting central or peripheral neurological diseases, cognitive or language impairments, psychiatric diagnoses, had undergone recent surgical procedures, or were taking medications that could affect cognitive function.

Procedures

Demographics, stroke characteristics (type, location, time since stroke onset, side of hemiparesis), and stroke interventions were documented. The National Institutes of Health Stroke Scale (NIHSS) was used to evaluate stroke severity [17]. MoCA [18], MMSE [19], CDT (according to Hendriksen) [20], Short Falls Efficacy Scale International [21], 36-Item Short Form Survey [22], and Barthel Index [23] were assessed.

The dual-task assessments were conducted in a clinical setting with the help of either a physical therapist or a research assistant. In all settings and combinations, the motor task was a 10-meter walk test (10MWT), performed under standardized conditions as described by Hosoi et al. [24], while the visual-verbal Stroop test served as the cognitive task. The dual-task assessment included the following combinations:

1. cognitive task performance;
2. motor task performance (10MWT) at a comfortable walking speed;
3. motor task performance (10MWT) at maximum walking speed;
4. simultaneous motor and cognitive task performance with prioritization of the cognitive task (cognitive prioritization);
5. simultaneous motor and cognitive task performance with prioritization of maximum walking speed (gait prioritization).

While the single-task cognitive performance was always assessed first, the other combinations involving a motor component

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Tab. 1. Classification of patterns of cognitive-motor dual-task interference (adapted from Plummer et al. [27]).

		Cognitive Performance		
		worsened	no change	improved
motor performance	worsened	mutual interference	cognitive-related motor interference	cognitive priority trade-off
	no change	motor-related cognitive interference	no dual-task interference	cognitive facilitation
	improved	motor-priority trade-off	motor facilitation	mutual facilitation

were performed in random order to prevent bias. Each of the combinations 2–5 was repeated twice, and the mean of the two repetitions (weighted in the case of the Stroop test by the number of questions answered) was used as the final measurement for each patient.

The visual-verbal Stroop test was projected onto a board placed 3 m in front of seated participants during the single-task condition and 16 m from the start marker of the 10MWT test during the dual-task condition [25]. The visual-verbal Stroop test involved sequentially presented events of either congruent or incongruent color words (e. g., the word ''yellow'' shown in blue letters). The colors yellow, red, blue, and green were used. Participants were required to name the color in which the word was displayed rather than reading the text. The displayed events progressed automatically without stopping, with a time interval varying between 0.8 s and 1.2 s to prevent rhythmic patterning. The visual-verbal Stroop test lasted 30 s in the single-task condition while participants were seated. In the dual-task setting, the video was projected for the entire duration of the 10MWT. To prevent learning effects, six different versions of the visual-verbal Stroop test were used, with congruent and incongruent stimuli presented in random order. All tests were recorded on a video camera (Panasonic HC-V380, Kadoma, Japan), capturing participants' verbal responses to the color words on the screen. Performance on the cognitive test was expressed as a percentage of correct words.

Calculating the dual-task effect and determining the pattern of dual-task interference

Cognitive-motor interference is traditionally quantified by calculating the dual-task effect (DTE) on a particular outcome of interest according to the following formula [26]:

DTE = (dual task performance – single task performance) / (single task performance) × 100

We calculated two sets of DTE values in our study: one for gait speed and the percentage of correct words with cognitive prioritization, and another for the same variables with gait prioritization. For each variable, negative DTE values indicate that performance worsened under dual-task conditions (i.e., dual-task cost), while positive values signify an improvement in the dual-task condition relative to single-task performance (i.e., dual-task benefit). As suggested by Subramaniam et al. [26], DTE values within the range of 0 ± 0.5 × standard deviation (SD) were considered non-interference (i.e., "no change"), whereas DTE values outside this range were classified as dual-task cost (worsened) or dual-task benefit (improved) concerning gait speed or the percentage of correct words in the cognitive task. After determining individual cognitive and motor interference, subjects were classified into one of nine pattern combinations, as specified in Tab. 1 [27]. Since the distribution of DTEs for the percentage of correct words in the cognitive task was highly asymmetric, a logarithmic indicator for cognition, "DTE log2," calculated as a base 2 logarithm of the ratio between dual-task and single-task performance (limited to the range of ± 3), was used as an alternative, producing an inherently symmetrical expression of the relative change.

Analysis and statistical methods

A majority of quantitative variables were found to be significantly non-normally distributed (based on a Shapiro-Wilk test); therefore, nonparametric methods were employed for analysis. When presenting descriptive statistics, mean and standard deviation (SD) or range are used for normally distributed variables, while median and quartiles are applied to non-normal ones. The percentage of correct words, walking speed, and their DTEs were compared between participant groups using Kruskal-Wallis ANOVA with the appropriate Bonferroni-corrected post-hoc test. Within each performance indicator, the values obtained under different conditions (single-task/dual-task, cognitive/gait priority) were compared within each group separately using Wilcoxon's matched-pairs test. The results of Wilcoxon's matched-pairs test are intentionally presented without Bonferroni correction, as the family of tests to which it could be applied can be defined in several ways, and given its mathematical simplicity, the correction can be easily applied ad hoc depending on the intended interpretation and its appropriate family definition. Mutual associations between categorical variables were evaluated by examining their mutual frequencies in a contingency table using Fisher's exact test. 95% confidence intervals (CI) for medians were determined through bootstrapping with 2000 samples. Statistical analysis was conducted using STATISTICA (version 11Cz; TIBCO Software Inc., Palo Alto, CA, USA), MATLAB (R2021a, The MathWorks Inc., Natick, MA, USA), and SISA (Simple Interactive Statistical Analysis, Hilversum, Netherlands). All P-values reported are two-tailed, with the threshold for statistical significance set at $\alpha = 0.05$.

Results

Table 2 provides an overview of the study participants' characteristics. The pMCI and ICA groups were divided based on MoCA, and the statistical significance of differences in cognitive ability was confirmed for the MMSE and CDT (both $P < 0.0001$). Regarding cognitive performance in the Stroop test, recorded values showed high variability, encompassing the entire range from 0 to 100%

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Tab. 2. Demographic characteristics of patients with post-stroke cognitive impairment, age-matched control groups with probable mild cognitive impairment and intact cognitive ability.

Parameter	Study Group			P-value for non-uniformity between 3 groups
	PSCI (N = 28)	pMCI (N = 25)	ICA (N = 25)	
age (mean, SD)	63.4 (12.1)	67 (10.3)	62.2 (8.5)	0.2384
sex (N, % female)	12 (42.9)	12 (48.0)	17 (68.0)	0.1713
BMI (median, 25–75%)	26.9 (25.6–28.6)	27.8 (25.4–28.8)	26.8 (24.3–29.0)	0.4778
education, years (median, 25–75%)	12.5 (11.5–14.5)	12.0 (12.0–13.0)	13.0 (12.0–17.0)	0.0942
MoCA Score (median, 25–75%)	22.0 (17.5–25.0)	24.0 (22.0–25.0)	26.0 (26.0–27.0)	–
MMSE (median, 25–75%)	20.0 (17.0–23.0)	23.0 (21.0–23.0)	26.0 (26.0–27.0)	< 0.0001
Clock Drawing Test (median, 25–75%)	1.0 (-1.0–3.0)	3.0 (2.0–3.0)	5.0 (5.0–6.0)	< 0.0001
Short FES (median, 25–75%)	7.0 (7.0–9.0)	7.0 (7.0–12.0)	7.0 (7.0–7.0)	0.1181
SF–36 (mean, SD)	50.3 (41.3–75.9)	71.9 (64.9–87.3)	78.0 (67.6–89.9)	0.0015
time since stroke, months (median, 25–75%)	4.0 (1.0–24.0)	–	–	–
NIHSS (median, 25–75%)	0.5 (0.0–2.0)	–	–	–
ischemic stroke onset, N (%)	28 (100)	–	–	–
arterial territory				
ACA, N (%)	4 (14.3)	–	–	–
MCA, N (%)	9 (32.1)	–	–	–
PCA, N (%)	7 (25)	–	–	–
subcortical, N (%)	8 (28.6)	–	–	–
side of hemiparesis, left (number, %)	13 (46.4)	–	–	–
Barthel index (median, 25%–75%)	95.0 (90.0–100.0)	–	–	–
presence of				
arterial hypertension, N (%)	19 (67.9)	–	–	–
coronary artery disease, N (%)	8 (28.6)	–	–	–
atrial fibrillation, N (%)	8 (28.6)	–	–	–
diabetes mellitus, N (%)	9 (32.1)	–	–	–
smoking history, N (%)	10 (35.7)	–	–	–
pre-event AT, N (%)	11 (39.3)	–	–	–
pre-event stroke, N (%)	12 (32.9)	–	–	–

ACA – anterior cerebral artery; AT – antithrombotic therapy; BMI – body-mass index; FES – Falls Efficacy Scale; ICA – group with intact cognitive abilities; MCA – middle cerebral artery; MMSE – Mini Mental State Examination; MoCA – Montreal Cognitive Assessment; mRS score – modified Rankin scale; N – number; NIHSS – National Institutes of Health Stroke Scale; PCA – posterior cerebral artery; pMCI – group with probable mild cognitive impairment; PSCI – group with post stroke cognitive impairment; SD – standard deviation

correct answers (Fig. 1a). The single-task condition revealed a statistically significant difference between the groups (P = 0.0004), with the ICA group markedly outperforming both the PSCI and pMCI groups. In the dual-task condition, all groups demonstrated a significant improvement in correct word percentages during both cognitive and gait prioritization compared to the single-task condition. Although still significant, this improvement was the smallest in the PSCI group, which therefore displayed the lowest percentage of correct words compared to pMCI and even more so compared to ICA in both cognitive and gait prioritization (both P < 0.0001).

Compared to cognitive performance, walking speed exhibited a much narrower distribution (Fig. 1b). A statistically significant difference was observed among the groups for all combinations of single- and dual-task conditions, as well as prioritization (all P < 0.0001). In all scenarios, the PSCI group performed the worst, followed by pMCI, with the ICA being the best performer. When comparing the dual-task condition to the corresponding single-task setting, all groups and prioritization strategies, except for the ICA group under cognitive prioritization, showed a statistically significant reduction in walking speed during the dual-task condition. The results also indicated a statistically significant improvement in walk-

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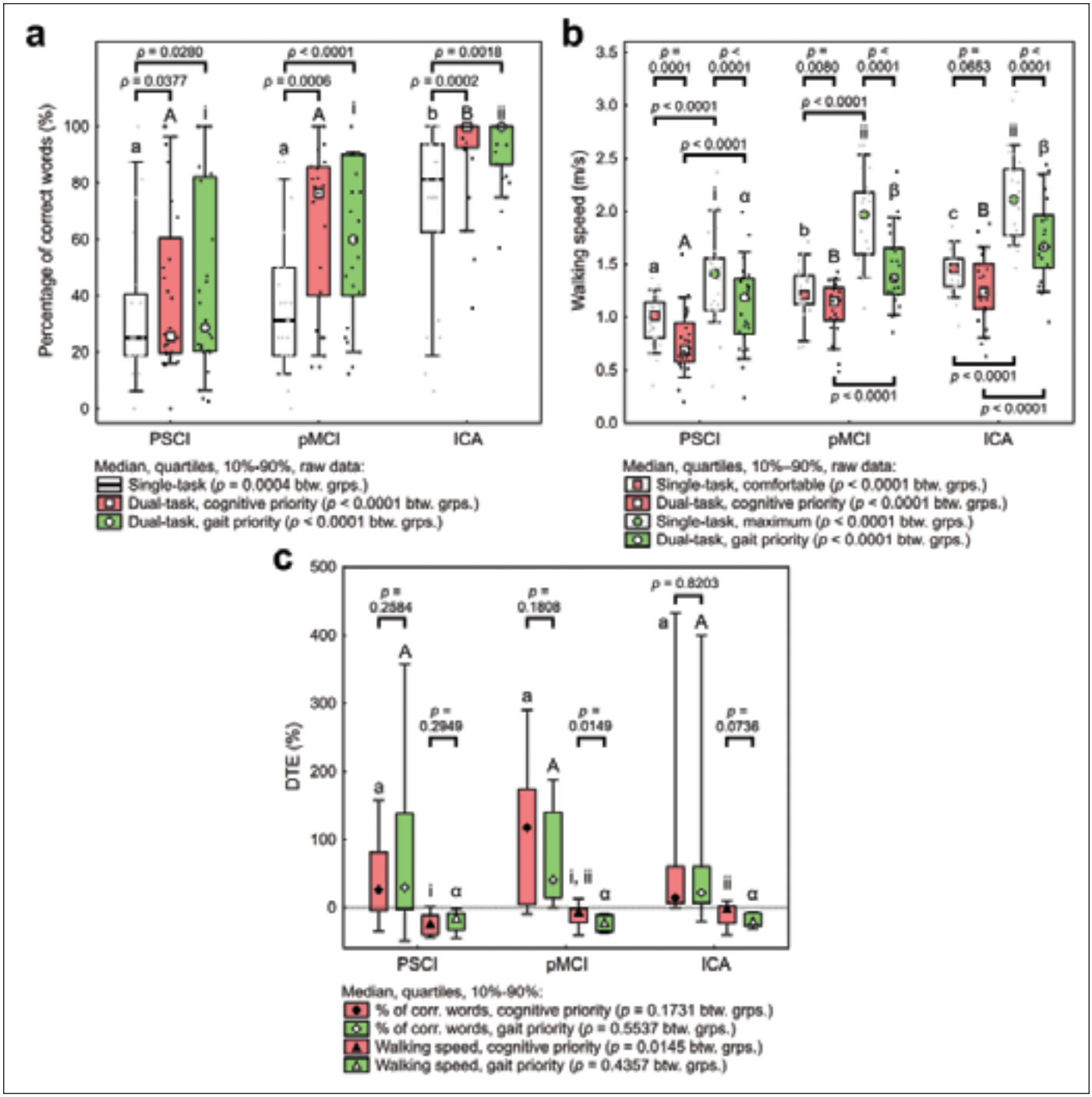


Fig. 1. Comparison of the percentage of correct words (a), walking speed (b), and their DTEs (c) between groups, single-/double-task conditions, and cognitive/gait prioritisation. P-values in the legends correspond to the Kruskal-Wallis test across the three groups, while the series of indices (a, b, c; A, B, C; i, ii, iii; α, β, γ) above the boxes indicate the results of the respective post-hoc tests (groups not sharing an index are significantly different at P < 0.05). The p-values in the charts were obtained using Wilcoxon's matched-pairs test without correction for multiple comparisons. For DTEs, raw data are not shown due to the extreme spread of outliers.

DTE – dual-task effect; ICA – group with intact cognitive abilities; pMCI – group of patients with probable mild cognitive impairment; PSCI – group of patients with post stroke cognitive impairment

Obr. 1. Porovnání procenta správně přečtených slov (a), rychlosti chůze (b) a relativního DTE (c) mezi skupinami za podmínek jednoduchého a dvojího úkolu při kognitivní prioritizaci a prioritizaci chůze. Hodnoty p v legendě odpovídají Kruskalovu-Wallisovu testu mezi třemi skupinami, indexy (a, b, c; A, B, C; i, ii, iii; α, β, γ) nad boxploty označují výsledky post hoc testů (skupiny bez společného indexu se statisticky významně liší při p < 0,05). Hodnoty p v grafech byly získány Wilcoxonovým párovým testem bez korekce na vícenásobná porovnání. Hodnoty DTE nejsou zobrazeny z důvodu extrémních odlehlých hodnot.

DTE – efekt dvojího úkolu; ICA – skupina s intaktními kognitivními funkcemi; pMCI – skupina pacientů s pravděpodobnou mírnou kognitivní poruchou; PSCI – skupina pacientů s kognitivní poruchou po CMP

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ing speed across all groups and conditions when gait priority or maximum speed was prioritized.

When assessed with DTE, the previously described decline in walking speed alongside improved Stroop test performance in the dual-task condition was confirmed (Fig. 1c). Compared to analyzing absolute outcomes, which showed significant differences between groups, the relative method using DTE produced much more consistent results – the groups exhibited only marginally significant non-uniformity in DTE for walking speed with cognitive prioritization ($P = 0.0145$). Notably, the pMCI group showed considerably poorer DTE for walking speed during gait prioritization compared to cognitive prioritization. Regarding the percentage of correct words in the Stroop test, DTE exhibited high variability (due to the inherent fluctuations in Stroop outcomes) and did not mirror the group differences observed in the dual-task responses in the absolute outcomes assessment.

When subjects were classified into the "improved" / "no change" / "worsened" categories based on the DTEs of their walking speed and Stroop test results, the overall trend was that cognitive performance either improved or remained stable, while gait performance declined when both tasks were performed simultaneously. Notably, cognitive prioritization was linked to significant differences among the three participant groups. Improved cognition was observed in 5 out of 28 patients in the PSCI group, 13 out of 25 in the pMCI group, and 5 out of 25 in the ICA group ($P = 0.0169$). Deterioration in walking speed was evident in 21 out of 28 members of the PSCI group, 11 out of 25 in the pMCI group, and 9 out of 25 in the ICA group ($P = 0.0087$). Conversely, gait prioritized dual-task settings had similar effects across all groups, with 7/28, 7/25, and 6/25 ($P = 1$) showing improved cognition, and 23/28, 23/25, and 23/25 ($P = 0.4931$) exhibiting worsened walking speed in PSCI, pMCI, and ICA, respectively.

After combining the individual cognitive and motor DTE categories, the resulting classification patterns of cognitive-motor interference (Fig. 2) confirmed that the choice of cognitive or gait prioritization altered the interference patterns during dual-task performance. Cognitive-related motor interference ($N = 17$ in all groups) and cognitive prioritization trade-offs ($N = 6$ in all groups) were the most common patterns in gait prioritization. The cognitive prioritization produced greater differences in interference patterns, particularly for the pMCI and ICA groups. The pMCI group showed an increased preference for cognitive facilitation ($N = 8$) compared to the ICA group, which exhibited more cases of no dual-task interference ($N = 11$). Paradoxically, cognitive prioritization resulted in more frequent cases of motor facilitation compared to gait prioritization across all groups.

Simultaneous visualization of both DTEs confirmed the tendencies observed earlier through the categorical approach, but also revealed a significantly asymmetric distribution of the DTE for the Stroop test outcome in both cognitive and gait prioritization (Fig. 3). This asymmetry was eliminated when the alternative DTE log2 was used for this outcome (Fig. 4a, b). Despite the considerable visual overlap of the point clusters, suggesting high similarity of interference patterns between PSCI, pMCI, and ICA, visualizing the cluster midpoints using median DTEs with 95% confidence intervals uncovered some separation between groups, which was notably greater under the cognitive prioritization condition (Fig. 4c, d).

Discussion

This study investigated the patterns of cognitive-motor interference in the PSCI, pMCI, and ICA groups. The heterogeneity of the stroke cohort (PSCI) should be considered when interpreting the findings. Post-stroke cognitive, sensory, and motor impairments are known to vary according to lesion characteristics, and different lesion locations may be associated with distinct cognitive deficits and postural control impairments. As these functions contribute substantially to cognitive-motor interference during dual-task conditions, lesion-related variability may have influenced the observed dual-task performance [28,29]. In the single-task condition, the baseline cognitive and motor performances of the groups differed. The PSCI group exhibited the lowest scores in correct answers and walking speed, followed by the pMCI group, with the ICA group showing the highest results. Because the groups were categorized based on cognitive abilities, different scores in the visual-verbal Stroop test were expected. This version of the Stroop test is commonly used to evaluate patterns of cognitive decline and the ability to inhibit cognitive interference [25]. Regarding motor function, the results supported a link between cognitive decline in pre-dementia stages and slower walking speed at baseline. Furthermore, mild cognitive impairment and reduced walking speed have been found to share a common decrease in hippocampal volume [30].

In the dual-task condition, all groups increased their correct answers on the Stroop test regardless of prioritization, and all groups except the ICA group in cognitive prioritization showed a reduction in walking speed. When evaluated using DTE, the previously mentioned decline in walking speed and the increased Stroop test performance in the dual-task condition were confirmed. For the percentage of correct words in the Stroop test, DTE showed high variability (due to the variability of Stroop outcomes themselves) and did not reflect the differences in the dual-task response observed between the groups in the absolute outcome assessment. The PSCI group, which had the greatest improvement (from 10% to 20%), started with a low or zero percentage of correct answers, whereas the ICA group began with a high percentage of correct answers with no room for improvement (from 90% to 100% Stroop). Participants maintained a high level of correct responses during the Stroop task in the dual-task condition, suggesting they focused on cognitive performance, as shown in previous studies [31,32].

Thus, all groups in our study did not behave according to the "posture first" hypothesis as predicted by the task prioritization model, which suggests prioritizing walking or balance over cognitive task performance in the dual-task condition [25]. Bloem et al. [33] reported that patients with neurological impairments tend to prefer the "posture second" strategy, where cognitive tasks are given precedence over walking, leading to an increased risk of falls, as observed in our study across all groups examined. The dual-task prioritization model indicates that the choice of prioritizing walking or cognitive performance during dual-task walking depends on an individual's physiological and cognitive capacity, as well as the postural, sensorimotor, and cognitive demands of the tasks [31]. This shift in DTE – from reduced gait speed with dual-tasking to prioritized cognition during the second trial – may be due to practice effects, which are defined as performance improvements resulting from repeated exposure and increased familiarity with the test. Although practice effects can potentially introduce error, they may also

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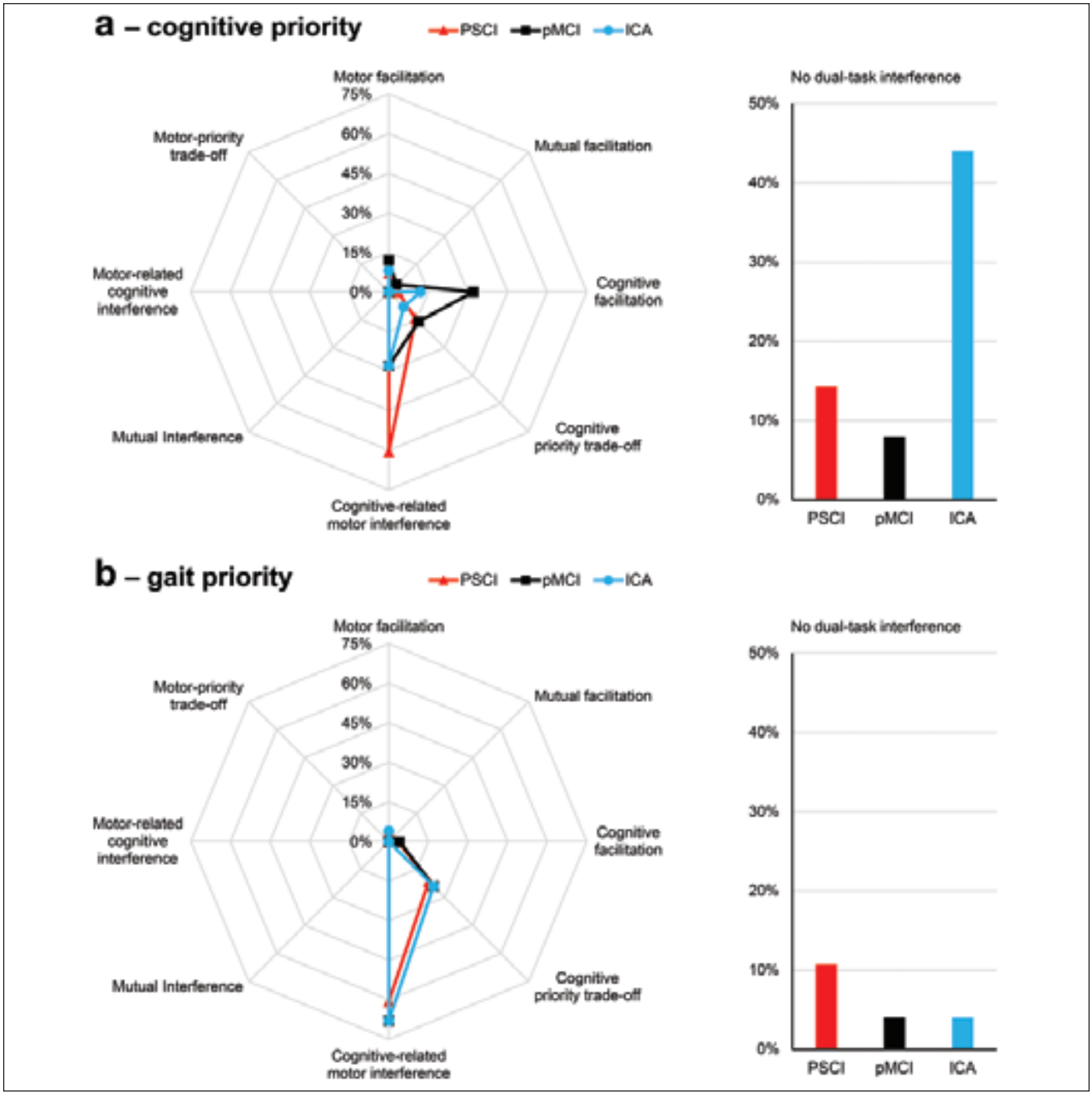


Fig. 2. Relative frequencies of individual cognitive-motor interference patterns during cognitive (a) and gait (b) prioritisation in PSCI, pMCI, and ICA groups. Patterns indicating some form of interference are displayed in radar plots with each interference pattern arranged on their 8 axes, and the distance of each point from the centre reflecting the relative frequency of that interference pattern. The shape of the polygon formed by connecting the resulting points illustrates the distribution of interference types within each group. The relative frequencies of non-interference cases are shown in bar charts on the right.

ICA – group with intact cognitive abilities; pMCI – group of patients with probable mild cognitive impairment; PSCI – group of patients with post stroke cognitive impairment

Obr. 2. Relativní četnosti jednotlivých vzorců kognitivně-motorické interference při kognitivní prioritizaci (a) a prioritizaci chůze (b) ve skupinách PSCI, pMCI a ICA. Jednotlivé vzorce interference jsou zobrazeny pomocí radarových grafů, v nichž každá osa odpovídá jednomu z osmi vzorců interference a vzdálenost bodu od středu vyjadřuje jeho relativní četnost. Tvar polygonu vzniklého propojením jednotlivých bodů znázorňuje distribuci jednotlivých typů interference v rámci každé skupiny. Relativní četnosti případů bez interference jsou znázorněny sloupcovými grafy v pravé části obrázku.

ICA – skupina s intaktními kognitivními funkcemi; pMCI – skupina pacientů s pravděpodobnou mírnou kognitivní poruchou; PSCI – skupina pacientů s kognitivní poruchou po CMP

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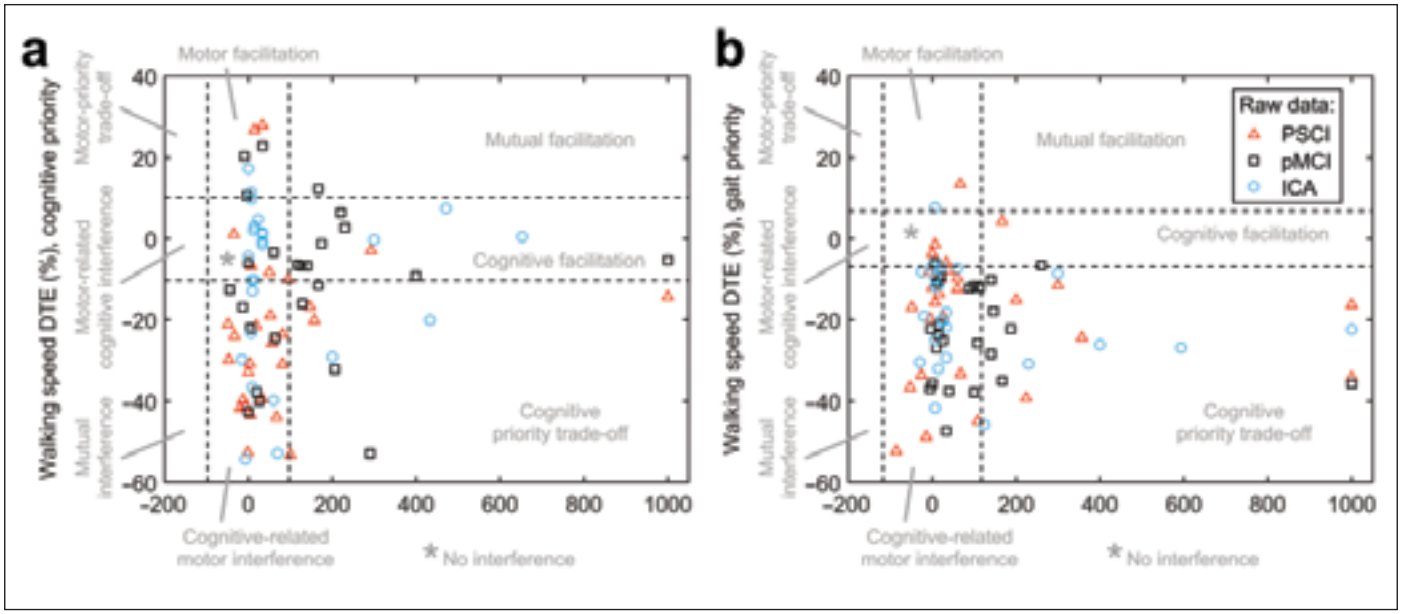


Fig. 3. Effects of dual-tasking on walking speed and the percentage of correct words in the visual-verbal Stroop test, with cognitive (a) and gait (b) prioritisation, alongside the corresponding classification of subjects into interference patterns. The charts on the left and right share the same scale for easy comparison. The legend applies to all charts.

DTE – dual-task effect; ICA – group with intact cognitive abilities; pMCI – group of patients with probable mild cognitive impairment; PSCI – group of patients with post stroke cognitive impairment

Obr. 3. Efekt dvojího úkolu na rychlost chůze a procento správně přečtených slov ve vizuálně-verbálním Stroopově testu při kognitivní prioritizaci (a) a prioritizaci chůze (b) s klasifikací podle vzorců kognitivně-motorické interference. Grafy vlevo a vpravo mají shodné měřítko pro usnadnění porovnání. Legenda je společná pro všechny grafy.

DTE – efekt dvojího úkolu; ICA – skupina s intaktními kognitivními funkcemi; pMCI – skupina pacientů s pravděpodobnou mírnou kognitivní poruchou; PSCI – skupina pacientů s kognitivní poruchou po CMP

hold prognostic value. The reduction of the interference effect during practice occurs regardless of age, but in the elderly, this reduction consistently happened throughout the training. Lower practice effects are associated with neurodegenerative biomarkers and future cognitive decline. Our study confirms this, as cognitive improvement was observed in only 5 of 28 patients in the PSCI group [34,35].

Dual-task prioritization strategies can be examined by adjusting task prioritization instructions. We confirmed that whether cognitive or gait prioritization was selected influenced interference patterns during dual-task performance across the PSCI, pMCI, and ICA groups. Interestingly, gait prioritization removed the differences observed between groups under cognitive prioritization. This evidence supports the greater diagnostic value of cognitive prioritization during dual-task assessment compared to gait prioritization. The ability to emphasize cognitive function during dual-task performance makes cognitive prioritization an ideal tool for reflecting the motor-cognitive interface. The beneficial effect of task prioritization can be explained by limited cognitive capacities and/or cognitive interference when two tasks compete for the same processing resources [12,14]. The cognitive prioritization led to larger differences in interference patterns, especially among the pMCI and ICA groups. The most common patterns involved cognitive-related motor interference and a trade-off with cognitive priority, but the MCI group showed a greater preference for cognitive facilitation compared to the ICA group, which experienced more cases without dual-task interference. Increasing evidence supports using dual-task assessments with cognitive prioritization as a tool to distinguish between different levels of cognitive impairment, as in our study [36,37]. Due to the limited attentional capacity of individuals with probable cognitive impairment, which hampers their cognitive abilities, interference in walking speed occurred when a visual-verbal Stroop test was added. Particularly for those with probable cognitive impairment, gait appeared to demand high levels of attention and required more cognitive resources, leading to greater dual-task decrements in this group [38].

The resulting classification patterns of cognitive-motor interference revealed that the most common patterns in gait and cognitive prioritization among post-stroke patients were cognitive-related motor interference and a trade-off in cognitive focus. These findings provide new evidence that different cognitive-motor interactions can occur in acute stroke survivors and that the chosen attention allocation strategy is likely influenced by task-level factors (such as difficulty or novelty) and person-level factors (such as cognitive and postural reserve) [37]. The frequent occurrence of cognitive-related motor interference during walking may suggest that post-stroke patients tend to prioritize attention on the cognitive task at the expense of gait performance. However, if slowing down is regarded as an adaptive safety strategy, it could be argued that members of the PSCI group were emphasizing postural control during walking. Therefore, it is reasonable to hypothesize that post-stroke patients who perceive the cognitive task as more challenging will, under dual-task conditions, prioritize this task over maintaining their usual walking speed [3]. Patients with

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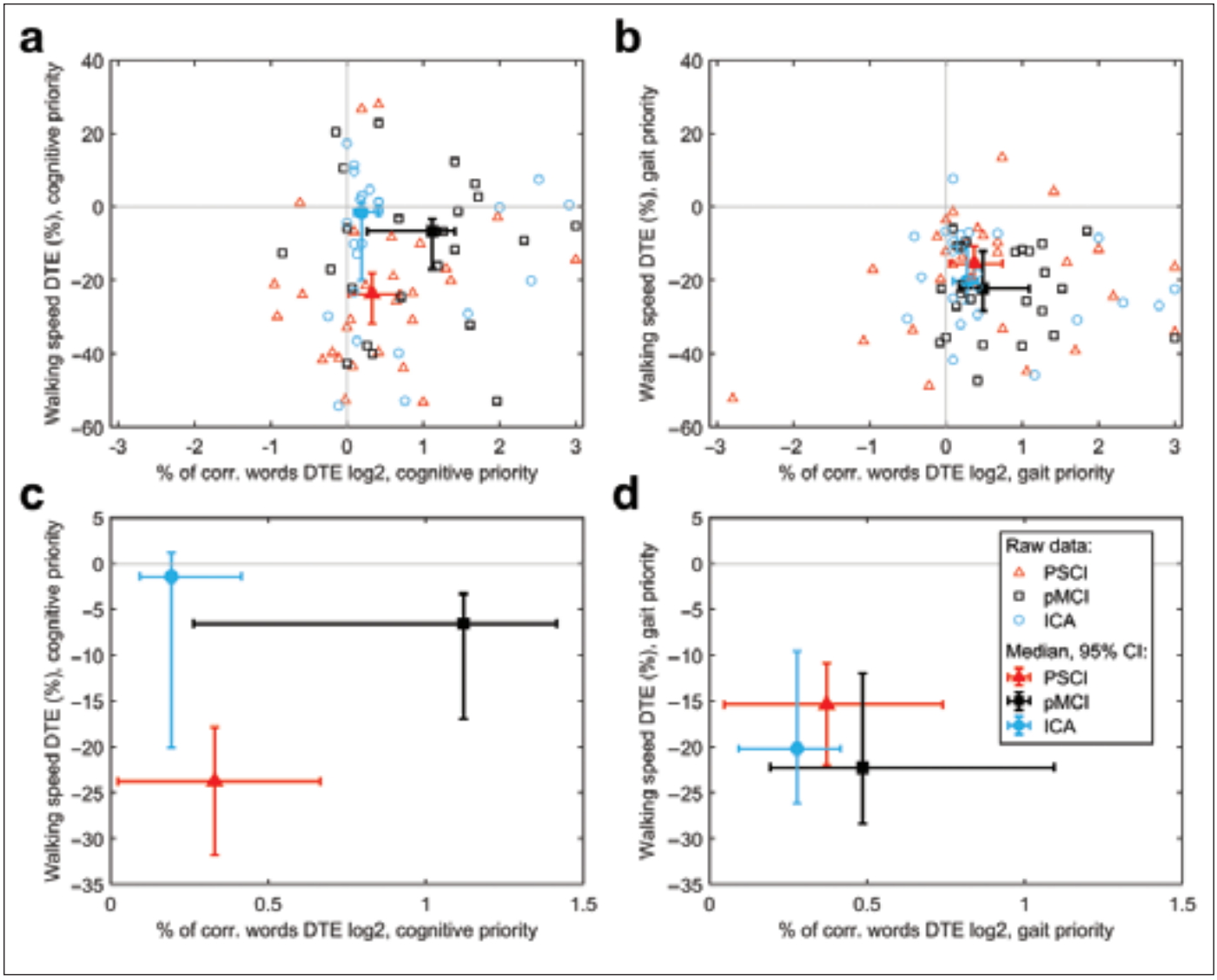


Fig. 4. Dual-task effects using the logarithmic measure of change DTE log 2 for the Stroop test outcomes (a, b). Group centroids estimated by medians in (a) and (b) are shown in detail with an increased scale in (c) and (d), respectively. Charts on the left and right have the same scale to enable direct comparison. The legend applies to all charts.

DTE – dual-task effect; ICA – group with intact cognitive abilities; pMCI – group of patients with probable mild cognitive impairment; PSCI – group of patients with post stroke cognitive impairment

Obr. 4. Efekt dvojího úkolu vyjádřený logaritmickou mírou změny DTE $\log_2$ pro výsledky vizuálně-verbálního Stroopova testu (a, b). Poloha jednotlivých skupin určená mediány na (a) a (b) je ve zvětšeném měřítku zobrazena v grafech (c) a (d). Grafy vlevo a vpravo mají shodné měřítko pro usnadnění porovnání. Legenda je společná pro všechny grafy.

DTE – efekt dvojího úkolu; ICA – skupina s intaktními kognitivními funkcemi; pMCI – skupina pacientů s pravděpodobnou mírnou kognitivní poruchou; PSCI – skupina pacientů s kognitivní poruchou po CMP

slower walking speeds after a stroke may lack the automaticity needed to 'free up' executive resources, thereby limiting their ability to improve dual-task walking. In contrast, those who walk faster may have greater executive resources available to enhance this ability. In fact, gait impairment – especially in individuals with cognitive impairment – has been observed even in stroke patients without leg weakness, coordination issues, or visuospatial problems [38].

Limitations and future directions

The first limitation of this study is that cognitive status was determined using the screening tools MoCA and MMSE. Consequently, group allocation represented a screening-based classification and should not be interpreted as a formal clinical diagnosis of cognitive impairment.

Due to variations in motor performance costs depending on the type of cognitive task, the study was limited by selecting only a single cognitive modality during dual-task performance. There is no assurance that differences in the tasks used truly reflect different levels of cognitive and/or motor difficulty, or the extent of increased difficulty these changes indicate. Another limitation of the study is the lack of standardization in dual-task paradigms, which may account for the heterogeneity of results. A recommendation for future research is to assess the Visual-Stroop test using a visuomotor reac-

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tion time during dual-task performance and to avoid the number of repetitions to prevent potential rapid learning effects.

Conclusion

The DTE evaluation confirmed a decline in walking speed and an increase in performance on the Stroop test, regardless of prioritization across all tested groups. The patterns most commonly observed in post-stroke patients were cognitive-related motor interference and the cognitive priority trade-off. Cognitive prioritization altered the patterns of interference during dual-task performance among PSCI, pMCI, and ICA groups. This evidence supports the greater diagnostic value of cognitive prioritization during dual-task assessment compared to gait prioritization. Our study endorses the use of dual-task examinations with cognitive prioritization as a tool to differentiate progression across various levels of cognitive impairment.

Ethical principles

The entire study was conducted in accordance with the Helsinki Declaration of 1975 (as revised in 2004 and 2008). The study received approval from the Ethical Committee of the University Hospital Pilsen and the Faculty of Medicine in Pilsen, approval ID: EK-516/23 (4. 1. 2024). All participants provided written informed consent to participate.

Availability of data and materials

The dataset supporting the conclusions of this article is available from the authors upon reasonable request. Iva Hereitová should be contacted for such requests via email: ivlckova@kfe.zcu.cz.

Conflict of interest

The authors declare they have no potential conflicts of interest concerning drugs, products, or services used in the study.

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