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Title: Factor structure of the Montreal Cognitive Assessment in Parkinson's disease.

Running title: MoCA factor structure in Parkinson's disease.

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Abstract

Objectives. The Montreal Cognitive Assessment (MoCA) is a common tool for screening mild cognitive impairment (MCI) and dementia. Studies in multiple clinical groups provide evidence for various factor structures mapping to different cognitive domains. We tested the factor structure of the MoCA in a large cohort of early Parkinson's disease (PD).

Materials and Methods. Complete MoCA data were available from an observational cohort study for 1738 patients with recent onset PD (64.6% male, mean age 67.6, SD 9.2). Confirmatory factor analysis (CFA) was applied to test previously defined two-factor, six-factor, and three-factor models in the full sample and in a subgroup with possible cognitive impairment (MoCA <26). Secondary analysis used exploratory factor analysis (EFA; principal factors with oblique rotation).

Results. The mean MoCA score was 25.3 (SD 3.4, range 10-30). Fit statistics in the six-factor model (χ^2/df 17.77, RMSEA 0.10, CFI 0.74, TLI 0.69, SRMR 0.07) indicated poorer fit than previous studies. Findings were similar in the two-factor and three-factor models. Exploratory factor analysis suggested an alternative six-factor solution (short-term recall, visuospatial-executive, attention/working memory, verbal-executive, orientation, expressive language), though CFA did not support the validity of the new model.

Conclusions. The factor structure of the MoCA in early PD was not consistent with previous research. This may reflect higher cognitive performance and differing demographics in our sample. The results do not support a clear, clinically relevant factor structure in an early PD group, suggesting that the MoCA should be followed with detailed assessment to obtain domain-specific cognitive profiles.

Keywords (MeSH)

Parkinson Disease/psychology; Cognition Disorders/psychology;
Factor Analysis, Statistical; Neuropsychological Tests; Psychometrics; Mental Status and Dementia Tests.

Key points

- Previously reported factor structures in the Montreal Cognitive Assessment do not show a good fit in a large cohort of people with early Parkinson's disease.
- The Montreal Cognitive Assessment has no clear, clinically relevant factor structure in this cohort.
- The Montreal Cognitive Assessment should be reserved for screening purposes; assessment of specific cognitive domains requires more detailed testing.

Introduction

The Montreal Cognitive Assessment (MoCA)[1] is a brief, clinician-administered test used to assess global cognitive function and to screen for dementia. It is also a sensitive screen for mild cognitive impairment (MCI)[1], a state of subtle cognitive deficits that is intermediate between normal ageing and dementia[2]. In addition to providing an index of global cognitive function, the MoCA was designed to assess performance in different cognitive domains, including memory, executive function, and visuospatial skills. The test was originally validated in Alzheimer's disease (AD)[1], and subsequently in diverse clinical groups, consistently showing superior psychometric properties to previous screens[3-6].

The MoCA has been widely used to evaluate MCI and dementia in Parkinson's disease (PD)[5]. Cognitive decline is associated with PD progression[7,8], though it is common at all stages of the disease, including the newly diagnosed[9]. In contrast to AD, where the primary impairment is to memory, PD-MCI and PD dementia (PDD) are characterised by dominant deficits in executive function and attention, reflecting the involvement of fronto-subcortical circuits[10]. The MoCA, which includes several executive and attentional items, has established reliability and validity in PD[11]. As a result, the Movement Disorder Society clinical diagnostic criteria for PD-MCI recommend the MoCA for use in PD[12].

Although the MoCA was designed to provide an indication of global cognitive function, it was structured around six cognitive domains, namely short-term recall, visuospatial abilities, executive function, language, attention/concentration/working memory (ACWM), and orientation to time and place[1]. A much fuller assessment of each of these domains is possible with detailed neuropsychological testing, which then identifies distinct cognitive profiles. However, such testing is time-consuming and resource-intensive. Identification of cognitive subtypes for clinical and research purposes would be greatly facilitated if a brief assessment such as the MoCA were capable of adequately distinguishing and quantifying

the different cognitive domains. To test if the MoCA is capable of this, its internal structure has been assessed more rigorously.

When applied to a sample including multiple dementia subtypes, confirmatory factor analysis (CFA) indicated that the MoCA comprised two distinct factors: memory and attentional-executive function[13]. The memory factor included short-term recall, language, and orientation subtests, and the attentional-executive factor included attention, executive, and visuospatial subtests. A later CFA focused on a more specific clinical sample (AD and MCI) and tested several models[14]. The two-factor memory/attentional-executive model had a good fit to the observed data, but the six-factor structure postulated by Nasreddine et al.[1] had a significantly better fit. Additionally, a single second-order factor ("cognition") was identified. This included all first-order factors, and supported the unidimensionality of the MoCA as a measure of global cognitive function[14].

There has been limited exploration of the construct validity of the MoCA in PD. One study found that the executive, visuospatial, and memory subsections showed high sensitivity against a detailed, domain-focused neuropsychological test battery, though specificity and accuracy was adequate only for the executive section[15]. So far, only a single factor analysis of the MoCA in PD has been published. The cohort in this study (n = 357) were highly educated, had a short mean disease duration, and a high mean MoCA score of 26.4. As a result, some items (primarily in the naming and orientation sections) showed clear ceiling effects, being correct in over 95% of cases. Because of the lack of variance, these items were omitted from the subsequent exploratory factor analysis (EFA), which suggested a three-factor model comprising executive function, memory, and verbal attention[16]. This model has not yet been independently tested with CFA.

The objective of this analysis was to extend previous research by exploring the factor structure of the MoCA in a very large cohort of people with PD, including patients with

possible MCI and dementia, in order to test its construct validity in this population. Previously reported models based on PD, AD, and other dementia cohorts formed the basis of the analysis.

Methods

Participants

Data was derived from the Tracking Parkinson's study, a long-term prospective observational project involving 1998 recent-onset (<3.5 years disease duration at study enrolment) participants at 72 sites with a diagnosis of PD[17]. The study was conducted in compliance with the Helsinki Declaration[18], and approved by the multicentre ethics committee and by local research and development departments. Exclusion criteria included age over 90 years, atypical parkinsonism, or a severe comorbid illness that would preclude full study participation. Patients with a clinical diagnosis of dementia were excluded, but cognitive function was otherwise not part of the eligibility criteria. For the current analysis, baseline data were used. Cases with incomplete MoCA data or blank values for education (n = 262) were excluded from analysis.

CFA models were applied to the full sample (n = 1738). Due to possible ceiling effects (which might obscure a meaningful factor structure), we also conducted the CFA analyses on two sub-samples defined by a MoCA score lower than 26, encompassing probable MCI and more severe levels of impairment (n = 797), and lower than 21, indicating moderate to severe cognitive impairment (n = 157). These cutoff values have been used previously and have good sensitivity and specificity[17,19].

Measures

The primary measure was the MoCA version 7.1. The assessment was conducted by local clinical and/or research staff (generally a research nurse). A copy of the test and the instruction manual are freely available online (www.mocatest.org). The MoCA takes approximately 5-10 minutes to administer, and includes items testing word recall, figure copying, clock drawing, trail-making, phonemic fluency, verbal abstraction, picture naming, sentence repetition, forward and backward digit span, vigilance, serial subtraction, and temporal and spatial orientation. Some MoCA items were only available as ordinal values: contour, hands, and numbers on the clock drawing task had been collapsed into a single item (scored 0-3), as had the serial subtractions (also 0-3). The highest possible MoCA score is 30. Higher scores indicate better cognitive function, and a score greater than 25 indicates normal cognition. If the subject has fewer than 13 years of education, one bonus point is added to the total score. The bonus point was included when reporting descriptive results for the total score and when identifying the MoCA<26 and MoCA<21 sub-samples, but the item scores used for the factor analysis were not adjusted for education level.

Education is reported dichotomously as more than 12 years of education versus fewer than 13 years of education. The first item of the Unified Parkinson's Disease Rating Scale (UPDRS 1.1) was used to assess the degree of functional impairment resulting from cognitive deficits. This was rated by the clinician on a five-point scale (none, slight, mild, moderate, severe), which were analysed as numeric values (0-4).

Statistical analysis

Statistical analysis was run on Stata version 13[20]. CFA with maximum likelihood estimation was used to test previously reported factor structures of the MoCA. Exploratory factor analysis (EFA; principal factors with oblique rotation) was used to identify possible alternative models. Because the MoCA item scores are not continuous, these analyses were based on summary statistics from correlation matrices. The EFA, and subsequent CFA of

the resulting model, were conducted on randomly-selected subgroups of the full sample; the similarity of these groups was confirmed using between-group comparisons (chi-square, t-test, Mann-Whitney U test) for sex, education, age, disease duration, functional impairment etc. Where necessary, the normality of the distribution was evaluated by inspecting a histogram.

The goodness-of-fit of each factor model was evaluated using the following indices: χ^2/df, comparative fit index (CFI), Tucker-Lewis Index (TLI), root mean square error of approximation (RMSEA), and standarised root mean square residual (SRMR). Approximate values indicative of a good fit were as follows: χ^2/df = 2-3, RMSEA < 0.05, CFI > 0.95, TLI > 0.95, and SRMR < 0.08[21].

The Stata syntax for the whole analysis is available online on the Open Science Framework [https://osf.io/x7d8p/].

Results

Sample characteristics

Descriptive statistics for the full sample and the MoCA<26 and MoCA<21 sub-samples are presented in Table 1. For all groups, functional impairment secondary to the cognitive symptoms was minimal. Men were overrepresented in the cohort, which is usual for PD samples[22]; this was more pronounced in the MoCA<26 and MoCA<21 sub-samples. The distribution of responses for each item are provided in Table S1. The highest percentage of correct answers were consistently provided for the orientation items; values for the recall items were typically lowest.

[INSERT TABLE 1 HERE]

Confirmatory factor analysis

Because some MoCA items were only available as ordinal values, polychoric correlation matrices were generated, as these accommodate both dichotomous and ordinal scores. Initially, these matrices had multiple blank values due to lack of variance in the data, precluding further analysis. Therefore, similar items were collapsed into additional ordinal variables, as follows: the lion, rhinoceros, and camel into a single "animals" item (scored 0-3); date, month, year, and day into a "temporal" [orientation] item (0-4); and place and city into a "spatial" [orientation] item (0-2). The polychoric correlation matrix for the full sample is provided in Table S2.

The polychoric correlation matrix was used to create a summary statistics dataset (SSD), which formed the basis of the CFA models. Factor-indicator correspondences used standard reflective measurement. Four CFA models based on previous research were tested: a two-factor model; a six-factor model; a one-factor second-order model based on the six-factor model; and a three-factor model based on 20 out of the 30 MoCA items (Table 2).

[INSERT TABLE 2 HERE]

The two-factor model included memory and attentional-executive function[13]. Factor loadings for the two-factor model in the full sample were varied, but all were statistically significant (Table S3).

The six-factor model comprised short-term recall, visuospatial abilities, executive function, ACWM, language, and orientation[14]. The model initially failed to converge. After noting that the "spatial" variable loaded perfectly onto the Orientation factor, we constrained that

variable's error variance to zero: this procedure enabled an admissible solution model to converge. Factor loadings were again universally significant, and tended to be stronger than the coefficients in the two-factor model (Table S4). Phonemic fluency was loaded onto two latent variables (executive function and language): for both, the coefficients were relatively weak.

The six-factor model formed the basis of a one-factor second-order model, again replicating Freitas et al.[14]. Again, the error variance for the "spatial" variable was constrained to zero. All of the first-order factors loaded strongly onto the higher-order factor ("cognition"), with the exception of orientation, which loaded more weakly. All loadings were statistically significant (Table S5).

The three-factor model excluded ten items that were also previously excluded in the original factor analysis[16] due to clear ceiling effects (specifically, the orientation, naming, and vigilance items). The subtractions test was cross-loaded onto both the executive and the verbal attention factors. All loadings were significant and coefficients were high, except for the loading of subtractions on verbal attention (Table S6).

Fit statistics were computed for all of the above models (Table 3); none had a good fit. When tested in the MoCA<26 subgroup, correlation coefficients and fit statistics in the two-factor and three-factor models were generally poorer (Tables S7-S9). The six-factor models failed to converge. With the MoCA<21 sub-group, all tested models failed to converge, possibly due to the limited sample size (n = 157). In each model, we explored various strategies with the aim of achieving convergence (e.g. examining modification indices and specifying better starting values), but the possible respecifications either could not be justified theoretically, or did not lead to convergence.

[INSERT TABLE 3 HERE]

Exploratory factor analysis

In order to determine whether the MoCA's items mapped to a different factor structure in this sample, we conducted an EFA. The full sample was split randomly into two subgroups of approximately equal size (Subgroup 1, n = 856; Subgroup 2, n = 882). The EFA was applied to Subgroup 1, and then tested with a CFA in Subgroup 2. Before the factor analysis was conducted, between-group comparisons were used to confirm that the subgroups were similar in relevant variables (age, disease duration, education, etc.); no significant differences were found.

The EFA model was constrained to six factors after examining a screeplot. Factors identified were short-term memory (comprising recall 1-5), executive-visuospatial function (cube, clock, trail-making, subtractions), attention and working memory (repetition 1, digit spans forward and backward, vigilance, and phonemic fluency), verbal-executive (abstraction 1 and 2 and phonemic fluency), orientation (temporal and spatial) and expressive language (repetition 2 and animals). Table 4 contains loadings for every item on every domain.

[INSERT TABLE 4 HERE]

The new model did not converge when tested with a CFA in Subgroup 2. Again, we explored various strategies designed to achieve convergence, but no appropriate respecifications emerged. Therefore, we were unable to validly compare the fit of the new model to previously tested ones. The model was not retained for further interpretation.

A second EFA replicating Benge et al.[16], constrained to three factors and excluding the orientation, naming, and vigilance items, was also conducted in Subgroup 1. The resulting

model was almost identical to that reported by Benge et al.[16], the sole exception being backward digit span, which loaded much more strongly onto the verbal attention factor rather than the executive factor. Subjecting this revised model to a new CFA in Subgroup 2 again found a poor fit (Table S10).

Discussion

In a large PD cohort, we did not find a clear factor structure in the MoCA. Six-factor and one-factor second-order models reported in AD and MCI samples[14], and a two-factor model reported in a varied dementia group[13], were not replicated in our cohort. Additionally, we found a poor fit for a three-factor model previously suggested as appropriate for PD. Finally, new EFA analyses conducted in our sample did not find a better structure to fit the observed data.

The discrepancy between our results and previous CFA models may be explicable by different cognitive score distributions in the samples tested. In our full sample, the mean MoCA score was 25.3, and 941 (54%) were in the normal range. In contrast, the samples in previous CFA analyses had much lower cognitive scores, with overall means of 14.4[13] and 22.4[14] in the cognitively impaired patients – in the latter study, the controls had a mean score of 24.7, below the recommended cutoff for healthy cognition. In both studies, the MCI groups would have been considered moderately to severely impaired in our analysis, as they had means of 19.6[13] and 18.3[14]. Moreover, our cohort differs from these in terms of education. More than two-thirds of our cohort had more than 12 education years, compared to only 11% of one previously tested sample[13]. In the other study, the mean number of education years was 7.8[14].

The EFA previously conducted in PD[16] was based on a cohort much more similar to our own; mean MoCA score, disease duration, education, and the ratio of men to women were

all comparable, though our cohort was slightly older on average. Our analysis found a poor fit for their model, showing that promising EFA models do not necessarily have a good fit when tested with CFA in independent samples. This was also the case for the new EFA models that we generated in our subgroup analyses. Similar to Benge et al.'s study[16], we found that the orientation, object naming, and digit span items had clear ceiling effects, reflecting their relative ease. Executive and memory items showed much greater variance, as was also the case for AD in Freitas et al.'s study[14]. Therefore, screening tests designed to be even shorter than the MoCA (i.e. 5 minutes or less) should minimally include sensitive tests of these two domains.

From this, it would appear that a clear factor structure to the MoCA may emerge in cohorts that are characterised by more severe cognitive impairment, where a consistent and theoretically reasonable pattern of errors might emerge. However, this factor structure is obscured in cognitively normal or mildly impaired samples, where by definition most participants will provide correct responses to the majority of the MoCA's items. We sought to test this hypothesis in a subset of our cohort with more severe impairment (MoCA<21), but the model failed to converge, potentially due to the small sample size. Future research with a larger cohort of moderately or severely impaired PD patients would be useful to establish whether the factor structure reported in other dementias is evident in this context.

The major strength of our analysis is the very large sample size (n = 1738), which permitted a well-powered sub-group analysis with a MoCA<26 sub-group (n = 797). However, a relatively large number of cases (n = 262) from the full dataset were excluded due to missing data. An additional limitation was that the sample was not fully representative of the PD population at large, given the eligibility criteria requiring diagnosis <3.5 years before study enrolment.

Our results suggest that the MoCA should be reserved for screening purposes, or for assessment of global level of cognitive function, as is suggested by the Movement Disorder Society[12]. The MoCA is a reliable and valid instrument for these purposes. However, detailed neuropsychological testing remains the gold standard for accurately measuring performance in different cognitive domains and subsequently describing an individual's cognitive profile.

Conclusion

In conclusion, our results do not support the existence of a clear factor structure to the MoCA in a large cohort of PD patients with overall normal or mildly impaired cognition. Comparisons to previous studies suggest that a clinically significant factor structure may emerge in samples with moderate to severe dementia. The MoCA may be useful for identifying meaningful subtypes in such cases, but our evidence suggests that it cannot do so in PD-MCI. Therefore, for the present, subtyping people with PD-MCI should rely on the established procedure of detailed neuropsychological testing. The MoCA should be used for either screening purposes or for assessing global cognitive function in PD.

Data availability statement

The data that support the findings of this study are available from the Tracking Parkinson's core committee. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the core committee.

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Tables

Table 1. Descriptive statistics for the full sample and sub-samples.

	Full sample	MoCA<26	MoCA<21
Sample size	1738	797	157
Age	67.6 (9.2)	69.9 (8.5)	73.4 (7.3)
Disease duration (years)	3.2 (3.1)	3.0 (2.7)	3.5 (4.1)
MDS UPDRS 1.1	0.5 (0.7)	0.7 (0.8)	0.9 (1.0)
MoCA total score	25.3 (3.4)	22.4 (2.7)	17.9 (2.2)
Male	1123 (64.6%)	564 (70.8%)	117 (74.5%)
>12 years education	1176 (67.6%)	492 (61.7%)	76 (48.4%)
<13 years education	562 (32.3%)	305 (38.3%)	81 (51.6%)

Data are n (%) or mean (standard deviation).

MDS = Movement Disorder Society, MoCA = Montreal Cognitive Assessment,

UPDRS = Unified Parkinson's Disease Rating Scale.

Table 2. Summary of models tested with confirmatory factor analysis.

Item	Two-factor model	Six-factor models	Three-factor model
Trail-making	Attentional-executive	Executive	Executive
Phonemic fluency	Attentional-executive	Executive*	Executive
Abstraction 1	Attentional-executive	Executive	Executive
Abstraction 2	Attentional-executive	Executive	Executive
Animals	Memory	Language	Not included
Repetition 1	Memory	Language	Verbal attention
Repetition 2	Memory	Language	Verbal attention
Recall 1	Memory	ST Recall	ST Recall
Recall 2	Memory	ST Recall	ST Recall
Recall 3	Memory	ST Recall	ST Recall
Recall 4	Memory	ST Recall	ST Recall
Recall 5	Memory	ST Recall	ST Recall
Digits forward	Attentional-executive	ACWM	Verbal attention
Digits backward	Memory	ACWM	Executive
Vigilance	Attentional-executive	ACWM	Not included
Subtractions	Attentional-executive	ACWM	Executive†
Cube	Attentional-executive	Visuospatial	Executive
Clock	Attentional-executive	Visuospatial	Executive
Temporal	Memory	Orientation	Not included
Spatial	Memory	Orientation	Not included

* Phonemic fluency was cross-loaded onto the language factor in the six-factor model. † Subtractions was cross-loaded onto the Verbal Attention factor. ACWM = attention, concentration, and working memory; ST = short term.

Table 3. Goodness-of-fit statistics for the confirmatory factor analyses.

Statistic	Two-factor model	Six-factor model	One-factor second-order model	Three-factor model
χ^2_M	4031.53	2753.84	2994.20	1623.26
df_M	169	155	164	101
p	<0.001	<0.001	<0.001	<0.001
$p_{close\text{-}fit\ H0}$	<0.001	<0.001	<0.001	<0.001
χ^2/df	23.86	17.77	18.26	16.07
RMSEA (90% CI)	0.115 (0.112-0.118)	0.098 (0.095-0.101)	0.100 (0.097-0.103)	0.093 (0.089-0.097)
CFI	0.62	0.74	0.72	0.81
TLI	0.57	0.69	0.68	0.77
SRMR	0.09	0.07	0.08	0.06

All models were tested in the full sample (n = 1738). CFI = comparative fit index, CI = confidence interval, RMSEA = root mean square error of approximation, SRMR = standardised root mean square residual, TLI = Tucker-Lewis Index.

Table 4. Factor loadings for each item on each cognitive domain by exploratory factor analysis.

Item	ST Memory	Visuospatial-executive	AWM	Verbal-executive	Orientation	Expressive language
Trail-making	0.03	**0.60**	0.03	0.04	0.13	-0.07
Phonemic fluency	0.03	0.08	**0.22**	**0.23**	0.13	0.06
Abstraction 1	-0.02	0.11	-0.08	**0.59**	0.14	0.02
Abstraction 2	0.06	0.06	-0.08	**0.68**	0.07	0.23
Animals	0.00	0.40	-0.06	0.13	-0.18	**0.45**
Repetition 1	0.04	0.00	**0.55**	0.09	-0.15	0.27
Repetition 2	0.06	-0.13	0.13	0.22	0.29	**0.53**
Recall 1	**0.35**	0.10	0.02	0.23	-0.10	-0.22
Recall 2	**0.65**	0.05	0.02	0.13	-0.11	-0.18
Recall 3	**0.69**	0.04	-0.01	0.06	-0.01	-0.05
Recall 4	**0.74**	-0.02	-0.01	-0.07	0.05	0.23
Recall 5	**0.74**	-0.05	-0.02	-0.05	0.04	0.19
Digits forward	-0.02	0.06	**0.72**	-0.12	-0.10	-0.07
Digits backward	-0.05	0.18	**0.48**	-0.18	0.27	0.18
Vigilance	0.05	-0.13	**0.32**	0.17	0.27	-0.06
Subtractions	-0.08	**0.33**	0.12	0.11	0.13	-0.03
Cube	-0.07	**0.53**	-0.06	0.24	0.05	0.08
Clock	0.08	**0.59**	0.15	-0.01	-0.18	0.08
Temporal	0.16	0.29	-0.08	-0.28	**0.45**	-0.09
Spatial	-0.05	-0.04	-0.08	0.17	**0.84**	0.08

This analysis was conducted on the full sample (Subgroup 1, n = 856). Values given as correlation coefficients. For each item, the strongest loading is in bold text.

AWM = attention and working memory; ST = short term.

Supplementary Material

Table S1. Distribution of responses for each MoCA item.

Item	Full sample	MoCA<26	MoCA<21
Trail-making	79.6	64.2	29.3
Phonemic fluency	67.8	52.8	30.6
Abstraction 1	79.8	66.8	37.6
Abstraction 2	82.0	70.6	44.6
Lion	99.5	99.0	97.5
Rhinoceros	91.2	86.2	72.6
Camel	98.9	97.9	94.9
Repetition 1	90.3	83.4	67.5
Repetition 2	82.5	70.8	51.6
Recall 1	50.9	29.2	9.6
Recall 2	64.2	40.8	19.1
Recall 3	54.9	29.3	8.3
Recall 4	41.9	18.9	5.1
Recall 5	54.3	29.4	10.2
Digits forward	95.3	91.3	84.1
Digits backward	90.6	83.8	67.5
Vigilance	88.5	79.9	65.0
Cube	76.6	60.0	29.3
Date	90.7	84.4	73.9
Month	99.3	98.9	97.5
Year	99.1	98.1	93.0
Day	98.4	96.7	91.7
Place	99.0	98.4	96.2
City	99.8	99.6	99.4
Subtractions (0 correct)	2.4	5.0	12.7
Subtractions (1 correct)	7.2	13.4	25.5
Subtractions (2-3 correct)	26.4	33.8	36.3
Subtractions (4-5 correct)	64.1	47.8	25.5
Clock (0 elements correct)	0.9	2.0	5.7
Clock (1 element correct)	4.5	9.9	23.6

Clock (2 elements correct)	18.5	29.9	42.7
Clock (3 elements correct)	75.6	58.2	28.0

All values are percentages (%). For all items except subtractions and clock, values represent correct responses.

Table S2. Polychoric correlation matrix for the full sample.

	Trail-making	Phonemic fluency	Abstraction 1	Abstraction 2	Animals	Repetition 1	Repetition 2	Recall 1	Recall 2	Recall 3	Recall 4	Recall 5
Trail-making	1											
Phonemic fluency	0.18	1										
Abstraction 1	0.30	0.25	1									
Abstraction 2	0.24	0.26	0.54	1								
Animals	0.34	0.12	0.19	0.24	1							
Repetition 1	0.26	0.25	0.26	0.22	0.09	1						
Repetition 2	0.22	0.23	0.25	0.30	0.22	0.50	1					
Recall 1	0.32	0.18	0.25	0.18	0.22	0.20	0.16	1				
Recall 2	0.27	0.20	0.26	0.24	0.15	0.24	0.22	0.54				
Recall 3	0.27	0.21	0.23	0.28	0.12	0.17	0.21	0.41	1			
Recall 4	0.24	0.21	0.21	0.22	0.21	0.19	0.23	0.27	0.45	1		
Recall 5	0.25	0.17	0.23	0.16	0.17	0.19	0.25	0.27	0.41	0.56	1	
Digits forward	0.10	0.19	0.26	0.07	0.06	0.38	0.19	0.16	0.20	0.20	0.23	1
Digits backward	0.34	0.24	0.18	0.18	0.22	0.25	0.16	0.19	0.08	0.17	0.13	0.17
Vigilance	0.25	0.26	0.16	0.20	0.15	0.14	0.25	0.22	0.15	0.26	0.20	0.25
Subtractions	0.31	0.13	0.20	0.26	0.13	0.10	0.10	0.17	0.16	0.17	0.11	0.16
Cube	0.50	0.24	0.29	0.33	0.30	0.25	0.25	0.22	0.22	0.29	0.18	0.42
Clock	0.44	0.17	0.22	0.23	0.26	0.21	0.19	0.22	0.25	0.29	0.25	0.24
Temporal	0.23	0.12	0.16	0.07	0.13	0.03	0.15	0.16	0.19	0.18	0.21	0.23
Spatial	0.20	0.15	0.21	0.19	0.13	0.17	0.34	–0.06	0.07	0.07	0.14	0.02

	Digits forward	Digits backward	Vigilance	Subtractions	Cube	Clock	Temporal	Spatial
Digits forward	1							
Digits backward	0.29	1						
Vigilance	0.23	0.34	1					
Subtractions	0.19	0.31	0.16	1				
Cube	0.22	0.20	0.23	0.31	1			
Clock	0.23	0.26	0.23	0.25	0.42	1		
Temporal	0.08	0.25	0.22	0.30	0.23	0.29	1	
Spatial	0.14	0.30	0.25	0.13	0.11	–0.01	0.37	1

Table S3. Factor loadings for each item by cognitive domain (two-factor model).

Item	Memory	Attentional-Executive
Trail-making		0.63 (0.02)**
Phonemic fluency		0.41 (0.02)**
Abstraction 1		0.54 (0.02)**
Abstraction 2		0.53 (0.02)**
Animals	0.32 (0.02)**	
Repetition 1	0.38 (0.02)**	
Repetition 2	0.42 (0.02)**	
Recall 1	0.54 (0.02)**	
Recall 2	0.67 (0.02)**	
Recall 3	0.72 (0.01)**	
Recall 4	0.67 (0.02)**	
Recall 5	0.66 (0.02)**	
Digits forward		0.37 (0.02)**
Digits backward	0.33 (0.02)**	
Vigilance		0.43 (0.02)**
Subtractions		0.43 (0.02)**
Cube		0.64 (0.02)**
Clock		0.57 (0.02)**
Temporal	0.35 (0.02)**	
Spatial	0.22 (0.03)**	

This model was tested in the full sample (n = 1738). Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$.

Table S4. Factor loadings for each item by cognitive domain (six-factor model).

Item	Executive	Language	ST Recall	ACWM	Visuospatial	Orientation
Trail-making	0.65 (0.02)**					
Phonemic fluency	0.29 (0.04)**	0.16 (0.05)*				
Abstraction 1	0.55 (0.02)**					
Abstraction 2	0.55 (0.02)**					
Animals		0.33 (0.03)**				
Repetition 1		0.63 (0.02)**				
Repetition 2		0.74 (0.02)**				
Recall 1			0.55 (0.02)**			
Recall 2			0.70 (0.02)**			
Recall 3			0.78 (0.01)**			
Recall 4			0.69 (0.02)**			
Recall 5			0.69 (0.02)**			
Digits forward				0.46 (0.02)**		
Digits backward				0.60 (0.02)**		
Vigilance				0.53 (0.02)**		
Subtractions				0.46 (0.02)**		
Cube					0.68 (0.02)**	
Clock					0.62 (0.02)**	
Temporal						0.37 (0.02)**
Spatial†						1.00 ($8.8x10^{-18}$)**

This model was tested in the full sample (n = 1738). Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$. † Error variance constrained to 0. ACWM = attention, concentration, and working memory; ST = short term.

Table S5. Factor loadings for each item by cognitive domain (one-factor second-order model).

Item	Executive	Language	ST Recall	ACWM	Visuospatial	Orientation
Cognition	0.99 (0.02)**	0.71 (0.03)**	0.60 (0.02)**	0.80 (0.02)**	0.85 (0.02)**	0.33 (0.02)**
Trail-making	0.62 (0.02)**					
Phonemic fluency	0.34 (0.05)**	0.12 (0.05)*				
Abstraction 1	0.57 (0.02)**					
Abstraction 2	0.56 (0.02)**					
Animals		0.34 (0.03)**				
Repetition 1		0.65 (0.02)**				
Repetition 2		0.70 (0.02)**				
Recall 1			0.54 (0.02)**			
Recall 2			0.69 (0.02)**			
Recall 3			0.78 (0.01)**			
Recall 4			0.69 (0.02)**			
Recall 5			0.69 (0.02)**			
Digits forward				0.46 (0.02)**		
Digits backward				0.60 (0.02)**		
Vigilance				0.53 (0.02)**		
Subtractions				0.46 (0.02)**		
Cube					0.70 (0.02)**	
Clock					0.60 (0.02)**	
Temporal						0.37 (0.02)**
Spatial†						1.00 (2.0×10^{-17})**

This model was tested in the full sample (n = 1738). Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$. † Error variance constrained to 0. ACWM = attention, concentration, and working memory; ST = short term.

Table S6. Factor loadings for each item by cognitive domain (three-factor model).

Item	Executive	ST Recall	Verbal Attention
Trail-making	0.66 (0.02)**		
Phonemic fluency	0.40 (0.02)**		
Abstraction 1	0.54 (0.02)**		
Abstraction 2	0.54 (0.02)**		
Repetition 1			0.77 (0.02)**
Repetition 2			0.62 (0.02)**
Recall 1		0.54 (0.02)**	
Recall 2		0.70 (0.02)**	
Recall 3		0.78 (0.02)**	
Recall 4		0.69 (0.02)**	
Recall 5		0.69 (0.02)**	
Digits forward			0.47 (0.02)**
Digits backward	0.44 (0.02)**		
Subtractions	0.45 (0.02)**		0.00 (0.00)
Cube	0.65 (0.02)**		
Clock	0.57 (0.02)**		

This model was tested in the full sample (n = 1738). Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$. ST = short term.

Table S7. Factor loadings for each item by cognitive domain (two-factor model, MoCA<26 sample).

Item	Memory	Attentional-Executive
Trail-making		0.56 (0.04)**
Phonemic fluency		0.15 (0.04)*
Abstraction 1		0.31 (0.05)**
Abstraction 2		0.35 (0.05)**
Animals	-0.06 (0.04)	
Repetition 1	-0.01 (0.04)	
Repetition 2	-0.01 (0.04)	
Recall 1	0.38 (0.04)**	
Recall 2	0.61 (0.03)**	
Recall 3	0.68 (0.03)**	
Recall 4	0.59 (0.03)**	
Recall 5	0.55 (0.03)**	
Digits forward		0.04 (0.04)
Digits backward	-0.15 (0.04)**	
Vigilance		0.16 (0.04)**
Subtractions		0.27 (0.04)**
Cube		0.41 (0.04)**
Clock		0.41 (0.04)**
Temporal	0.00 (0.04)	
Spatial	-0.13 (0.04)*	

Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$.

Table S8. Factor loadings for each item by cognitive domain (three-factor model, MoCA<26 sample).

Item	Executive	ST Recall	Verbal Attention
Trail-making	0.59 (0.04)**		
Phonemic fluency	0.16 (0.04)**		
Abstraction 1	0.33 (0.05)**		
Abstraction 2	0.36 (0.05)**		
Repetition 1†			1.00 ($3.7x10^{-16}$)**
Repetition 2			0.44 (0.03)**
Recall 1		0.37 (0.04)**	
Recall 2		0.61 (0.03)**	
Recall 3		0.68 (0.03)**	
Recall 4		0.60 (0.03)**	
Recall 5		0.55 (0.03)**	
Digits forward			0.31 (0.03)**
Digits backward	0.28 (0.04)**		
Subtractions	0.28 (0.04)**		
Cube	0.61 (0.04)**		
Clock	0.40 (0.04)**		

This model was tested in the full sample (n = 1738). Values given as correlation coefficient (standard error). * $p < 0.05$, ** $p < 0.001$. † Error variance constrained to 0. ST = short term.

Repetition 1 loaded almost perfectly onto Verbal Attention, preventing the model from converging. Therefore, this item's variance was constrained to 0.

Table S9. Goodness-of-fit statistics for the confirmatory factor analyses (MoCA<26 sample).

Statistic	Two-factor model	Three-factor model
χ^2_M	1966.62	796.32
df_M	169	102
p	<0.001	<0.001
$p_{close\text{-}fit\ H0}$	<0.001	<0.001
χ^2/df	11.64	7.80
RMSEA (90% CI)	0.116 (0.111-0.120)	0.092 (0.086-0.098)
CFI	0.35	0.64
TLI	0.27	0.58
SRMR	0.10	0.07

CFI = comparative fit index, CI = confidence interval, RMSEA = root mean square error of approximation, SRMR = standardised root mean square residual, TLI = Tucker-Lewis Index.

Table S10. Goodness-of-fit statistics for the confirmatory factor analysis (new three-factor model).

Statistic	New three-factor model
χ^2_M	1613.51
df_M	101
p	<0.001
$p_{close\text{-}fit\ H0}$	<0.001
χ^2/df	15.98
RMSEA (90% CI)	0.130 (0.125-0.136)
CFI	0.69
TLI	0.64
SRMR	0.09

CFI = comparative fit index, CI = confidence interval, RMSEA = root mean square error of approximation, SRMR = standardised root mean square residual, TLI = Tucker-Lewis Index.