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Individual differences in cognitive processes underlying Trail Making Test-B performance in old age: The Lothian Birth Cohort 1936

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A R T I C L E I N F O

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A B S T R A C T

The Trail Making Test Part B (TMT-B) is commonly used as a brief and simple neuropsychological assessment of executive dysfunction. The TMT-B is thought to rely on a number of distinct cognitive processes that predict individual differences in performance. The current study examined the unique and shared contributions of latent component variables in a large cohort of older people. Five hundred and eighty-seven healthy, community-dwelling older adults who were all born in 1936 were assessed on the TMT-B and multiple tasks tapping cognitive domains of visuospatial ability, processing speed, memory and reading ability. Firstly, a first-order measurement model examining independent contributions of the four cognitive domains was fitted; a significant relationship between TMT-B completion times and processing speed was found ($\beta = -0.610$, $p < .001$). Secondly, a bifactor model examined the unique influence of each cognitive ability when controlling for a general cognitive factor. Importantly, both a general cognitive factor (*g*; $\beta = -0.561$, $p < .001$) and additional *g*-independent variance from processing speed ($\beta = -0.464$, $p < .001$) contributed to successful TMT-B performance. These findings suggest that older adults' TMT-B performance is influenced by both general intelligence and processing speed, which may help understand poor performance on such tasks in clinical populations.

1. Introduction

The Trail Making Test (TMT) is widely used in clinical and research settings as a quick and easy assessment of aspects of executive function (Delis, Kaplan, & Kramer, 2001; Lezak, 1995; Reitan & Wolfson, 1993). The TMT consists of two parts: in Part A, individuals are required to draw a line connecting a series of encircled numbers in numerical order; and in Part B, individuals draw a line connecting a series of encircled numbers and letters, switching between ascending numerical and alphabetical order (i.e., 1, A, 2, B, 3, C and so on). In both TMT-A and TMT-B, participants are asked to complete the trail as quickly and as accurately as possible, with any errors highlighted and corrected as they happen (Lezak, 1995; Reitan & Wolfson, 1993). Part A of the TMT is administered to provide a baseline assessment of motor and visual search speed whereas Part B is administered as a measure of executive abilities, assessing set-shifting and inhibition (Arbuthnott & Frank, 2000; Gläscher et al., 2012; Kortte, Horner, & Windham, 2002; Strauss, Sherman, & Spreen, 2006).

Whereas the TMT is typically and widely used to assess executive dysfunction, it was originally designed to assess general intelligence and formed part of the Army Individual Test Battery (1944). Research has shown that scores on the TMT are strongly associated with intelligence, with the association with IQ being more evident in TMT-B compared to TMT-A (Dodrill, 1987; Warner, Ernst, Townes, Peel, & Preston, 1987). TMT scores have been found to correlate highly with intelligence, where individuals with lower IQ scores take longer to complete the TMT (Corrigan & Hinkeldey, 1987; Hagenaars et al., 2018). In a principal component analysis of neuropsychological test data (including the TMT) derived from 259 adults aged 18–94 years, Salthouse, Fristoe, and Rhee (1996) demonstrated that 47% of the variance was accounted by a first principal component. As all measures had moderately high loadings on this component, the authors concluded that a considerable amount of the total variance in the variables was shared with a general cognitive ability (*g*) factor. Moreover, a close relationship has been found between tasks assessing executive function and fluid intelligence abilities (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Salthouse, 2005), with differences between frontal patients and healthy controls largely or entirely accounted for by performance on tests of fluid intelligence (Roca et al., 2010; Woolgar et al., 2010).

Another feature of the TMT is that age effects are consistently

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reported on TMT-A and TMT-B (Giovagnoli et al., 1996; Hamdan & Hamdan, 2009; Hashimoto et al., 2006; Hester, Kinsella, Ong, & McGregor, 2005; Periáñez et al., 2007; Seo et al., 2006). Whereas both parts of the TMT show a similar age-related decline earlier in life, TMT-B completion times decline significantly more than TMT-A once older adults reach their seventies (Drane, Yuspeh, Huthwaite, & Klingler, 2002; Rasmusson, Zonderman, Kawas, & Resnick, 1998). For example, Rasmusson et al. (1998) analyzed the TMT data of 667 healthy older adults aged 60–96 years and found slower TMT-A and TMT-B completion times with age. However, when 385 of the participants were reassessed 2 years later, they were significantly slower on Part B but not Part A, with older adults demonstrating the most change.

Successful performance on the TMT is thought to rely on several distinct cognitive processes, including executive function and fluid intelligence. Therefore, it is important to understand which processes predict age-related differences in TMT-B performance. Cognitive ageing is not only associated with declines in executive processes (MacPherson, Phillips, & Della Sala, 2002; Mittenberg, Seidenburg, O'Leary, & DiGiulio, 1989; West, 1996), but also other cognitive processes thought to be associated with TMT-B performance (Salthouse, 2011a, 2011b). Regression analyses have revealed that tests tapping processing speed and working memory mediate some of the age effects on TMT-B performance (Oosterman et al., 2010; Sánchez-Cubillo et al., 2009) as well as episodic memory (Oosterman et al., 2010), verbal ability (Knight, McMahon, Greene, & Skeaff, 2006), arithmetic and visuomotor and visuospatial ability (Christidi, Kararizou, Triantafyllou, Anagnostouli, & Zalonis, 2015).

Salthouse (2011a) carried out detailed modelling of a TMT variant called the Connections Test (Salthouse et al., 2000) to examine the influence of fluid abilities, processing speed, vocabulary and episodic memory on performance. In this task, participants are presented with a 7 × 7 array containing neighboring targets to minimize visual search and motor movement. Salthouse (2011a) used a contextual analysis model to examine which of the latent constructs of fluid cognitive ability, memory, speed and vocabulary were involved in performance in a large group of adults aged 18 to 98 years on the simple (i.e., similar to TMT-A) and alternating (i.e., similar to TMT-B) versions of the Connections Test, and the extent to which the age differences in these two TMT versions were independent of age differences in the latent variables. Salthouse (2011a) reported that performance on the simple and alternating conditions of the Connections Test were strongly associated with fluid cognitive abilities (as measured using reasoning and spatial visualization tests), but also processing speed, with no unique contribution from working memory. In a second study, Salthouse (2011b) reported that fluid cognitive abilities and processing speed predicted performance on the Connections Test across two-time points approximately 2.5 years apart in both younger and older adults. Individuals who changed the most in terms of their fluid abilities and processing speed longitudinally were also those who were inclined to change the most in terms of performance on the Connections Test.

Whereas Salthouse (2011a) assessed the specific effects associated with latent variables representing fluid ability, episodic memory, processing speed, and vocabulary (i.e., variables based on the shared variance across test scores) on Connections Test performance, he did not account for the variance common to all cognitive test scores in the form of a general cognitive ability factor. Salthouse (2011a) suggested that fluid cognitive abilities and processing speed are important for TMT-B performance, but his work did not determine whether this is because of their association with general cognitive ability or whether these latent variables offer unique contributions. The degree to which fluid cognitive ability *and* processing speed contribute *uniquely* to TMT-B performance beyond their mutual covariance in older adults remains unknown. A more optimal approach would be to assess TMT-B's association with general cognitive function (*g*) and any additional association with cognitive domains that were orthogonal to *g*.

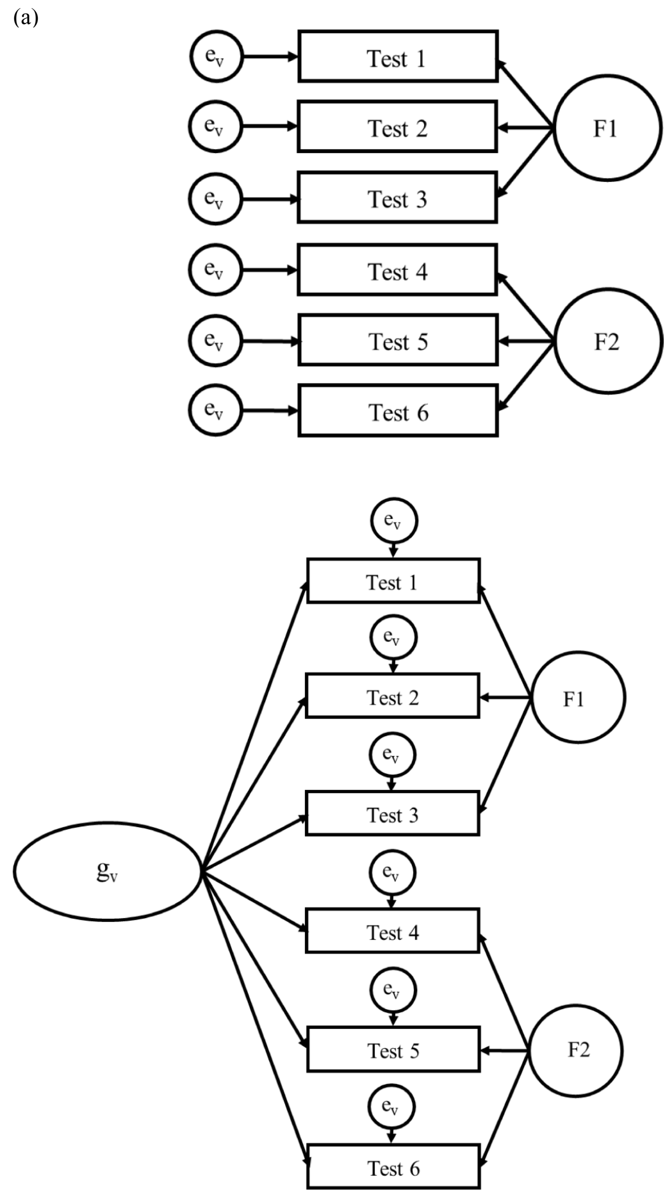

Fig. 1. Diagrammatic representations of variance decomposition in two structural equation models for estimating the association between cognitive ability and TMT-B performance. (a) A first-order factor model and (b) A bifactor model, including separate general and specific ability latent factors. Rectangles = observed variables; circles = latent variables; single-headed arrows = direct paths; gv = general cognitive ability variance; ev = error variance.

One method which allows for the examination of the shared and unique contributions of cognitive abilities to TMT-B performance is structural equation modelling (SEM). Here, several cognitive tests are used to estimate latent cognitive ability factors based on the shared variance across test scores and simultaneously the latent cognitive factors can be associated with TMT-B performance. Fig. 1a and b provide a diagrammatic representation of how TMT-B variance can be examined using either a first-order (as in Salthouse, 2011a), or a bifactor model of cognitive ability. Fig. 1a portrays a first-order factor model where the proportion of variance that is attributable to specific ability variance is modelled. However, this model only determines the

Table 1
Descriptive characteristics of demographics and cognitive test raw scores (N = 587) and correlational analyses with age at testing and TMT-B completion times (corrected and uncorrected for age).

Variable	Mean(SD) or Count (%) [a]	Complete (%)	Age correlation r (p-value)	TMT-B correlation r (p-value)	TMT-B age corrected correlation r (p-value)
Age at testing	76.23(0.67)	100			
Sex (Male/Female)	299(50.9)/288(49.1) [a]	100	0.04 (0.36)	0.05 (0.20)	0.05 (0.24)
Years of Education	10.81(1.14)	100	−0.08 (0.04)	−0.19 (< .01)	−0.18 (< .01)
HADS	2.69(2.18)	100	< .01 (0.90)	0.22 (< .01)	0.22 (< .01)
MMSE	28.84(1.29) [b]	100	−0.08 (0.06)	−0.35 (< .01)	−0.35 (< .01)
MHT age 11 IQ	101.99(14.84) [b]	94.5	−0.05 (0.23)	−0.44 (< .01)	−0.43 (< .01)
MHT IQ at testing	63.42(9.24)	99.1	−0.10 (0.01)	−0.58 (< .01)	−0.58 (< .01)
TMT-B completion time	97.73(44.27)	100	0.11 (< .01)		
Visuospatial ability					
Matrix reasoning	13.17(4.86)	99.7	< .01 (0.86)	−0.40 (< .01)	−0.40 (< .01)
Block design	32.65(9.72) [c]	99.5	−0.06 (0.16)	−0.41 (< .01)	−0.40 (< .01)
Spatial span forwards	7.63(1.66)	99.8	0.01 (0.77)	−0.29 (< .01)	−0.30 (< .01)
Spatial span backwards	7.14(1.57) [c]	99.8	0.10 (0.01)	−0.29 (< .01)	−0.30 (< .01)
Processing speed					
Symbol search	25.12(6.09)	99.8	−0.12 (< .01)	−0.55 (< .01)	−0.55 (< .01)
Digit symbol	55.05(12.27) [b]	99.7	−0.15 (< .01)	−0.57 (< .01)	−0.56 (< .01)
Inspection time	110.42(12.25) [c]	96.6	−0.15 (< .01)	−0.36 (< .01)	−0.35 (< .01)
Simple RT	−0.28(0.05)	99.8	−0.03 (0.53)	−0.31 (< .01)	−0.31 (< .01)
Choice RT	−0.67(0.09)	99.8	−0.06 (0.13)	−0.48 (< .01)	−0.48 (< .01)
Memory					
Logical memory (immediate)	46.33(10.51) [b]	99.5	−0.09 (0.02)	−0.33 (< .01)	−0.32 (< .01)
Logical memory (delayed)	29.18(8.3)	99.5	−0.08 (0.04)	−0.34 (< .01)	−0.33 (< .01)
Verbal paired associates (immediate)	20.37(7.67) [b]	96.9	< .01 (0.96)	−0.30 (< .01)	−0.30 (< .01)
Verbal paired associates (delayed)	6.29(2.05) [b]	96.8	−0.03 (0.46)	−0.27 (< .01)	−0.27 (< .01)
Digit span backwards	7.88(2.37)	99.7	−0.02 (0.65)	−0.34 (< .01)	−0.34 (< .01)
Reading ability					
NART	35.32(7.88) [b]	100	−0.08 (0.05)	−0.37 (< .01)	−0.37 (< .01)
WTAR	41.24(6.91) [b]	100	−0.13 (< .01)	−0.38 (< .01)	−0.37 (< .01)
TOPF	20.52(4.61)	73.4	−0.04 (0.46)	−0.36 (< .01)	−0.36 (< .01)

[b]female > male, [c]female < male
Note: HADS = Hospital Anxiety and Depression Scale; MMSE = Mini Mental State Examination; MHT = Moray House Test; NART = National Adult Reading Test; WTAR = Wechsler Test of Adult Reading; TOPF = Test of Premorbid Functioning.

associations with TMT-B that are driven by specific cognitive abilities and not general ability. Bifactor models allow for the simultaneous measurement of both specific and general cognitive abilities (Gignac, 2008; Schmiedek & Li, 2004; Brunner, Nagy, & Wilhelm, 2012; see Reise, Moore, & Haviland, 2010; Yung, Thissen, & McLeod, 1999). Fig. 1b depicts a bifactor model where a latent general cognitive ability factor (*g*) is estimated based on all test scores which have significant loadings, whilst specific ability latent factors are estimated from a subgroup of test scores assumed to measure each specific ability. This model allows us to look at the contribution of *g* and then specific cognitive capabilities that are statistically independent of *g*. To our knowledge, our study is the first to examine simultaneously the associations between TMT-B performance and general cognitive ability and specific abilities - with the latter being uncorrelated with general cognitive ability - using a bifactor modelling approach.

The present study addressed this question in a large, well-characterized cohort of older people in the UK known as the Lothian Birth Cohort 1936 (LBC1936; Deary et al., 2007; Taylor, Pattie, & Deary, 2018). These individuals have been comprehensively assessed on a number of cognitive tests in later adulthood, including TMT-B, and therefore we were able to use detailed modelling to examine the latent constructs that contribute to TMT-B performance in the LBC1936 cohort. In the current study, multiple tasks tapping the cognitive domains of visuospatial ability, processing speed, memory, and reading ability were administered to extract the variance common to each of these components and examine their shared and independent contributions to TMT-B performance, above and beyond the contribution of a general cognitive ability factor. Given that several of these cognitive processes are influenced by age, and are not statistically independent from one another, independent contributions to TMT-B performance are particularly of interest.

2. Method

2.1. Participants

The participants were 587 community-dwelling older adults (299 men, 288 women) who were members of the Lothian Birth Cohort 1936 (LBC1936). These cohort members were born in 1936 and most had been administered the Moray House Test (MHT) No. 12 of verbal and other types of reasoning at school as part of the Scottish Mental Survey 1947. Around age 70, 1091 surviving cohort members were recruited into Wave 1 of the LBC1936 as previously detailed (Deary et al., 2007). They then underwent triennial assessment at age 73 (LBC1936 Wave 2) and 76 years (LBC1936 Wave 3; Deary, Gow, Pattie, & Starr, 2012; Taylor et al., 2018). At Wave 3, they were also administered the TMT-B. For the current study, participants were selected from Wave 3 (around age 76) if they had a score of 24 or greater on the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975), a score of < 11 on the depression scale of the Hospital Anxiety and Depression Scale (HADS; Zigmond & Snaith, 1983), and had no self-report of stroke or neurodegenerative disease. These exclusion criteria resulted in 89 participants from Wave 3 not being included in our study. The mean age was 76.23 years (SD = 0.67; range = 74.59–77.70) and the mean number of years of full-time education was 10.81 (SD = 1.14; range = 8–14). Written informed consent was obtained from each participant prior to testing in accordance with departmental participant testing guidelines and the Declaration of Helsinki. The study was approved by the Lothian Research Ethics Committee (LREC/2003/2/39), the Scotland A Research Ethics Committee (07/MRE00/58), and the

Table 2
Correlation matrix of the cognitive test scores.

Study variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. TMT-B completion time		−.399	−.405	−.293	−.288	−.554	−.570	−.360	−.310	−.479	−.326	−.341	−.296	−.275	−.342	−.373	−.380	−.365
2. Matrix reasoning	< .001		.550	.304	.345	.422	.353	.249	.217	.217	.294	.288	.300	.265	.361	.419	.388	.389
3. Block design	< .001	< .001		.333	.397	.518	.389	.311	.214	.306	.236	.207	.167	.123	.282	.381	.353	.358
4. Spatial span forwards	< .001	< .001	< .001		.411	.301	.243	.170	.133	.298	.138	.150	.121	.133	.266	.135	.128	.124
5. Spatial span backwards	< .001	< .001	< .001	< .001		.313	.208	.178	.134	.220	.226	.227	.116	.106	.242	.134	.144	.123
6. Symbol search	< .001	< .001	< .001	< .001	< .001		.622	.357	.262	.473	.302	.299	.230	.226	.310	.365	.351	.364
7. Digit symbol	< .001	< .001	< .001	< .001	< .001	< .001		.345	.298	.513	.359	.374	.286	.243	.308	.395	.376	.359
8. Inspection time	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.222	.316	.125	.159	.151	.135	.144	.134	.164	.132
9. Simple RT	< .001	< .001	< .001	.001	.001	< .001	< .001	< .001		.436	.149	.210	.210	.158	.190	.234	.213	.204
10. Choice RT	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.223	.245	.216	.203	.206	.186	.166	.144
11. Logical memory (immediate)	< .001	< .001	< .001	.001	< .001	< .001	< .001	.003	< .001	< .001		.877	.458	.432	.322	.425	.419	.393
12. Logical memory (delayed)	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.506	.476	.268	.393	.380	.366
13. Verbal paired associates (immediate)	< .001	< .001	< .001	.004	.006	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.857	.283	.387	.371	.375
14. Verbal paired associates (delayed)	< .001	< .001	.003	.001	.012	< .001	< .001	.002	< .001	< .001	< .001	< .001	< .001		.283	.334	.337	.287
15. Digit span backwards	< .001	< .001	< .001	< .001	< .001	< .001	< .001	.001	< .001	< .001	< .001	< .001	< .001	< .001		.393	.426	.420
16. NART	< .001	< .001	< .001	.001	.001	< .001	< .001	.001	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.893	.840
17. WTAR	< .001	< .001	< .001	.002	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001		.824
18. TOPF	< .001	< .001	< .001	.010	.011	< .001	< .001	.007	< .001	.003	< .001	< .001	< .001	< .001	< .001	< .001	< .001	

Note: Pearson's *r* (upper diagonal) and *p*s (lower diagonal) are reported. NART = National Adult Reading Test; WTAR = Wechsler Test of Adult Reading; TOPF = Test of Premorbid Functioning.

Multi-Centre Research Ethics Committee for Scotland (MREC/01/0/56).

2.2. Cognitive tests

The LBC protocol article (Deary et al., 2007) provides full details for most of the cognitive tasks included in this current study. Part B of the Trail Making Test (TMT-B) was administered according to the standard administration instructions (Bowie & Harvey, 2006). The only difference was that all TMT-B completion times were considered, rather than only those completion times that were < 300 s.

Our latent cognitive variables were based on those previously derived by Tucker-Drob, Briley, Starr, and Deary (2014) in the LBC1936 cohort: i.e., visuospatial ability, processing speed, memory, and crystallized ability (referred to here as reading ability). Visuospatial ability was assessed using Matrix Reasoning and Block Design from the Wechsler Adult Intelligence Scale-Third Edition (WAIS–III; Wechsler, 1998a) and Spatial Span Forward and Spatial Span Backward from the Wechsler Memory Scale-Third Edition (WMS–III; Wechsler, 1998b). Processing speed was constructed using Symbol Search and Digit Symbol from the WAIS–III, Simple Reaction Time (Deary, Der, & Ford, 2001), Choice Reaction Time (Deary et al., 2001) and the psychophysical test Inspection Time (Deary et al., 2004). Simple Reaction Time requires participants to press a button as soon as a zero appears on the computer screen and Choice Reaction Time requires individuals to press one of four corresponding buttons in response to the presentation of digits 1–4. Inspection Time requires participants to indicate which of two vertical lines presented for various durations is longer. Memory was assessed using Logical Memory and Verbal Paired Associates from the WMS-III and Digit Span Backwards from the WMS-III. Reading ability was measured using the National Adult Reading Test (NART; Nelson & Willison, 1991) and the Wechsler Test of Adult Reading (WTAR; Wechsler, 2001), and the Test of Premorbid Functioning (TOPF; Wechsler, 2011). The latter, which was published in the same year as the start of Wave 3 and consequently introduced shortly after the commencement of that Wave, only included items that did not overlap with the WTAR.

2.3. Data analysis

Unless otherwise stated, all statistical analyses were performed in R version 3.3.3. The cognitive test scores were standardized for analysis. Scale directions were arranged so that higher scores represented better task performance on all cognitive variables except TMT-B completion times, where higher scores indicated poorer performance (i.e., longer completion times). Whereas some scores were missing, this was assumed to be completely at random and, therefore, no missing data were imputed.

The visuospatial ability, processing speed, memory, and reading ability latent variables were constructed using a structural equation modelling approach, based on the indicator variables discussed above (Tucker-Drob et al., 2014). Initially, a first-order model was defined which contained the specific cognitive abilities as factors. The specific cognitive ability factors were allowed to correlate, but no general cognitive factor was included. Second, a bifactor model was defined which contained both a general cognitive ability factor, and specific cognitive ability factors which, importantly, were uncorrelated with the general cognitive factor. In the bifactor model, each subtest score was loaded on both the general cognitive ability factor and a specific factor; this model accounts for a test's variance that is general (shared with all other tests), and for variance independent of the general factor that is shared with tests in the same specific cognitive domain. In both models, the input data were corrected for age and sex.

The psychometric structure of TMT-B completion times was modelled using MPlus version 6.1 (Muthén & Muthén, 1998–2012). Full information maximum likelihood (FIML) estimation under the

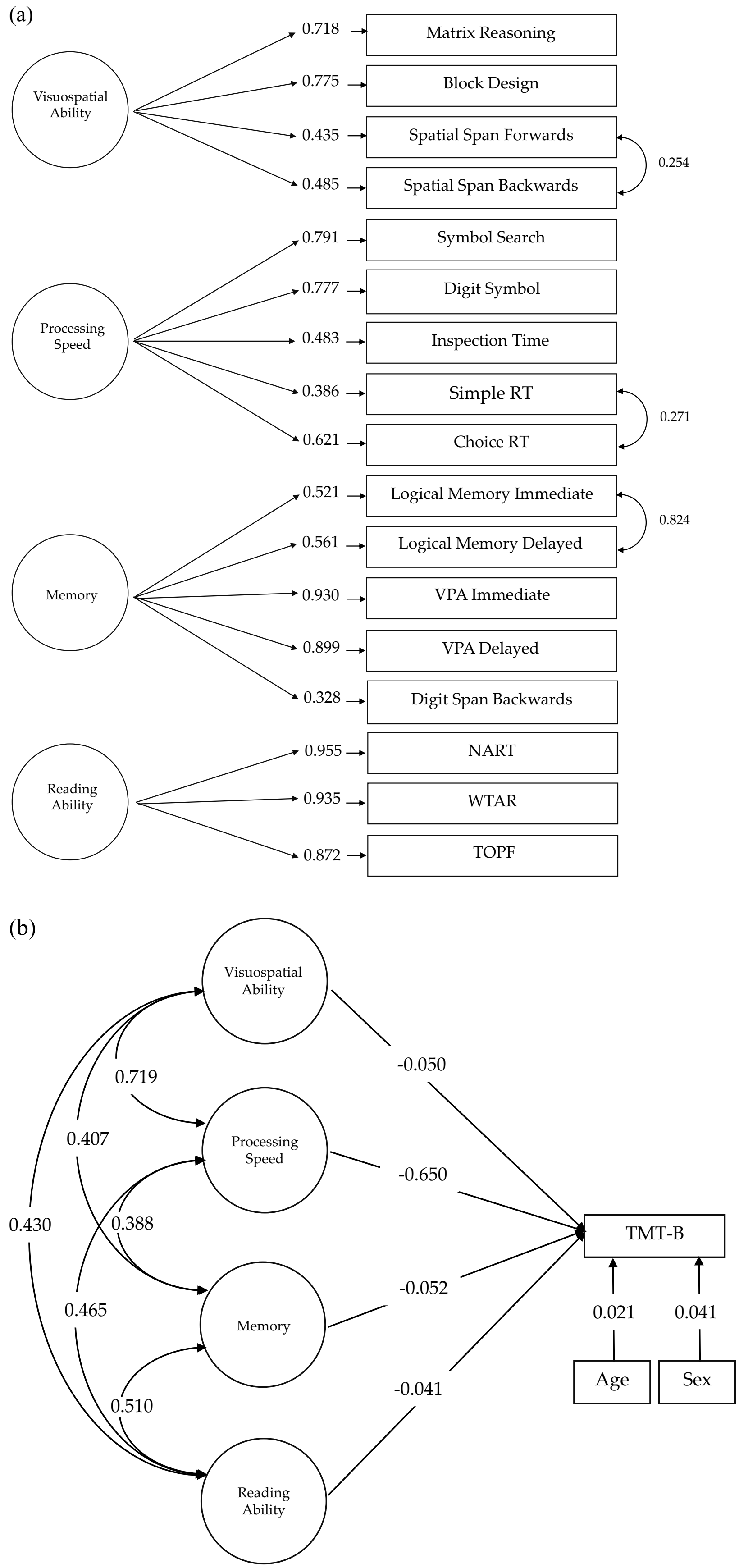

Fig. 2. Measurement and structural components of the same first-order model of age- and sex-adjusted associations between cognitive domains and TMT-B completion time. (a) The measurement model describes the loadings of cognitive test scores on the cognitive domains – note that the factors are correlated but this is not indicated here (b) The structural aspect of the first-order model depicts associations between the cognitive domains (as measured in Fig. 2a) and TMT-B, as well as the correlations between latent factors. Paths with double headed arrows denote covariance between indicators. VPA = Verbal Paired Associates; NART = National Adult Reading Test; WTAR = Wechsler Test of Adult Reading; TOPF = Test of Premorbid Functioning.

Table 3
Age- and sex-adjusted correlations between the latent factors representing visuospatial ability, processing speed, memory and reading ability in the first-order model of TMT-B completion times.

	1.	2.	3.	4.
1. Visuospatial ability		0.034	0.046	0.039
2. Processing speed	0.719		0.042	0.039
3. Memory	0.388	0.407		0.037
4. Reading ability	0.510	0.465	0.430	

Note: The upper diagonal contains the Pearson correlation coefficients and the lower diagonal contains the corresponding standard errors. All p-values were < .001.

Table 4
Age- and sex-adjusted regression coefficients for the first-order model of TMT-B completion times measured by visuospatial ability, processing speed, memory and reading ability.

		Est	SE	p-value
Visuospatial ability	Matrix reasoning	0.718	0.028	< .001
	Block design	0.775	0.027	< .001
	Spatial span forwards	0.435	0.039	< .001
	Spatial span backwards	0.485	0.037	< .001
Processing speed	Symbol search	0.791	0.021	< .001
	Digit symbol	0.777	0.022	< .001
	Inspection time	0.483	0.037	< .001
	Simple RT	0.386	0.039	< .001
	Choice RT	0.621	0.030	< .001
Memory	Logical memory (immediate)	0.521	0.033	< .001
	Logical memory (delayed)	0.561	0.031	< .001
	Verbal paired associates (immediate)	0.930	0.013	< .001
	Verbal paired associates (delayed)	0.899	0.013	< .001
	Digit span backwards	0.328	0.039	< .001
Reading ability	NART	0.955	0.007	< .001
	WTAR	0.935	0.008	< .001
	TOPF	0.872	0.012	< .001
TMT-B completion time	Visuospatial ability	−0.050	0.070	0.471
	Processing speed	−0.650	0.061	< .001
	Memory	−0.052	0.039	0.185
	Reading ability	−0.041	0.042	0.324
	Age	0.021	0.031	0.502
	Sex	0.041	0.032	0.198

Note: All estimates are fully standardized regression coefficients.

assumption of Missing at Random was used to deal with missing data. Model fit was assessed based on the comparative fit index (CFI) and the root mean square error of approximation (RMSEA).

3. Results

The descriptive characteristics and bivariate associations between the observed scores for the cognitive tests are shown in Tables 1 and 2. Even in this narrow-age cohort, those participants who were older when they attended the cognitive testing appointment achieved significantly lower scores on TMT-B, Spatial Span Backwards, Symbol Search, Digit Symbol, Inspection Time, Logical Memory Immediate and Delayed, and WTAR. All cognitive tests had moderate to high negative correlations with TMT-B completion times, regardless of the domain they assess (r = 0.27 to 0.58, all ps < .01). Better performance on all cognitive tests was associated with faster TMT-B completion times. TMT-B completion times correlated most highly with the contemporaneous MHT IQ (r = −0.58), and the paper and pencil speed tests (i.e., Symbol Search, r = −0.55, and Digit Symbol, r = −0.57). All cognitive tests, irrespective of their latent variable domain, significantly correlated with one another (rs ≥ 0.11, all ps ≤ .01).

Initially, a first-order measurement model with the four cognitive domains was fitted and then a bifactor model. In both models, several of the latent variables contained subtests that provided two scores (i.e., Verbal Paired Associates Immediate and Delayed recall, Logical Memory Immediate and Delayed recall, Forwards and Backwards Spatial Span, and Simple and Choice RT). These subtest scores share test-specific variance, which would not be anticipated to be explained by the latent variable. Both subtest scores were included as manifest variables, and their residuals were allowed to covary.

The fit indices for the first-order model were: χ^2 = 549.77, df = 147, CFI = 0.930, RMSEA = 0.068. In Fig. 2a, the measurement model depicts the factor structure for the latent cognitive domains (i.e., visuospatial ability, processing speed, memory and reading ability). In Fig. 2b, the structural model focuses specifically on the age- and sex-adjusted associations between each latent cognitive domain and TMT-B (for visualization purposes, it does not show the modelled interrelations among subtests and domains/factors).

Correlations between the latent factors of the first-order model are presented in Table 3. All four cognitive ability factors strongly positively correlated with one another (range = 0.39 to 0.72; M = 0.49). Table 4 demonstrates the age- and sex-adjusted regression coefficients for the first-order model. Each cognitive test only loaded onto one latent factor with no cross-loadings (β ≥ .328, ps < .001).

In the first-order model, only processing speed was significantly associated with TMT-B performance (β = −0.650, p < .001) (Fig. 2b). Visuospatial ability (β = −0.050, p = .471), memory (β = −0.052, p = .185) and reading ability (β = −0.041, p = .324) were not associated with TMT-B performance.

In the bifactor model, the fit indices were within the desired ranges: χ^2 = 323.19, df = 129, CFI = 0.966, RMSEA = 0.051. Fig. 1b shows a diagrammatic representation of a bifactor model including separate general and specific ability latent factors. Fig. 3a presents the measurement model depicting the cognitive ability factors and their variables. Fig. 3b shows the structural model focusing on the age- and sex-adjusted associations between TMT-B and the latent cognitive domains, where the common variance (g) on all test scores is, in effect, statistically removed. In other words, this bifactor model allows us to test associations between TMT-B and g and also with the latent cognitive domains; these domains (on the left-hand side of Fig. 3b) are orthogonal to g (which represents the shared variance across all cognitive tests) and thus g has effectively been partialled out of the cognitive domains. As in previous figures, the interrelations among the subtests (the four correlated residuals were the same as those in the first-order model) and latent domains/factors, this time depicted in Fig. 3a, are not shown.

Table 5 shows the correlations between the latent factors of the bifactor model of TMT-B completion times. In the bifactor model, the factor loadings of each subtest on g were generally moderate to large (> 0.40). Highest loadings (> 0.60) were found for Matrix Reasoning (0.65), Block Design (0.66), NART (0.82), WTAR (0.80) and TOPF (0.75). Loadings of 0.40 or lower were found for Simple RT (0.31), Choice RT (0.34), Inspection Time (0.31), Verbal Paired Associates immediate recall (0.39), Verbal Paired Associates delayed recall (0.33), Spatial Span Forwards (0.35) and Spatial Span Backwards (0.39). Table 6 demonstrates the factor loadings of each subtest on the general factor. The mean general factor loading was 0.51.

Table 7 and Fig. 3b show the age- and sex-adjusted regression coefficients for the bifactor model. In this model, in which shared covariance among each of the individual cognitive tests is represented by g, there was a significant and large association between TMT-B completion time and g (β = −0.561, p < .001). Notably, a significant association between the cognitive domain of processing speed and TMT-B completion time was also found in the same model (β = −0.464, p < .001). None of the other associations with the domain-specific factors were significant (β ≤ 0.066, ps ≥ .808). These results suggest that processing speed uniquely accounts for some

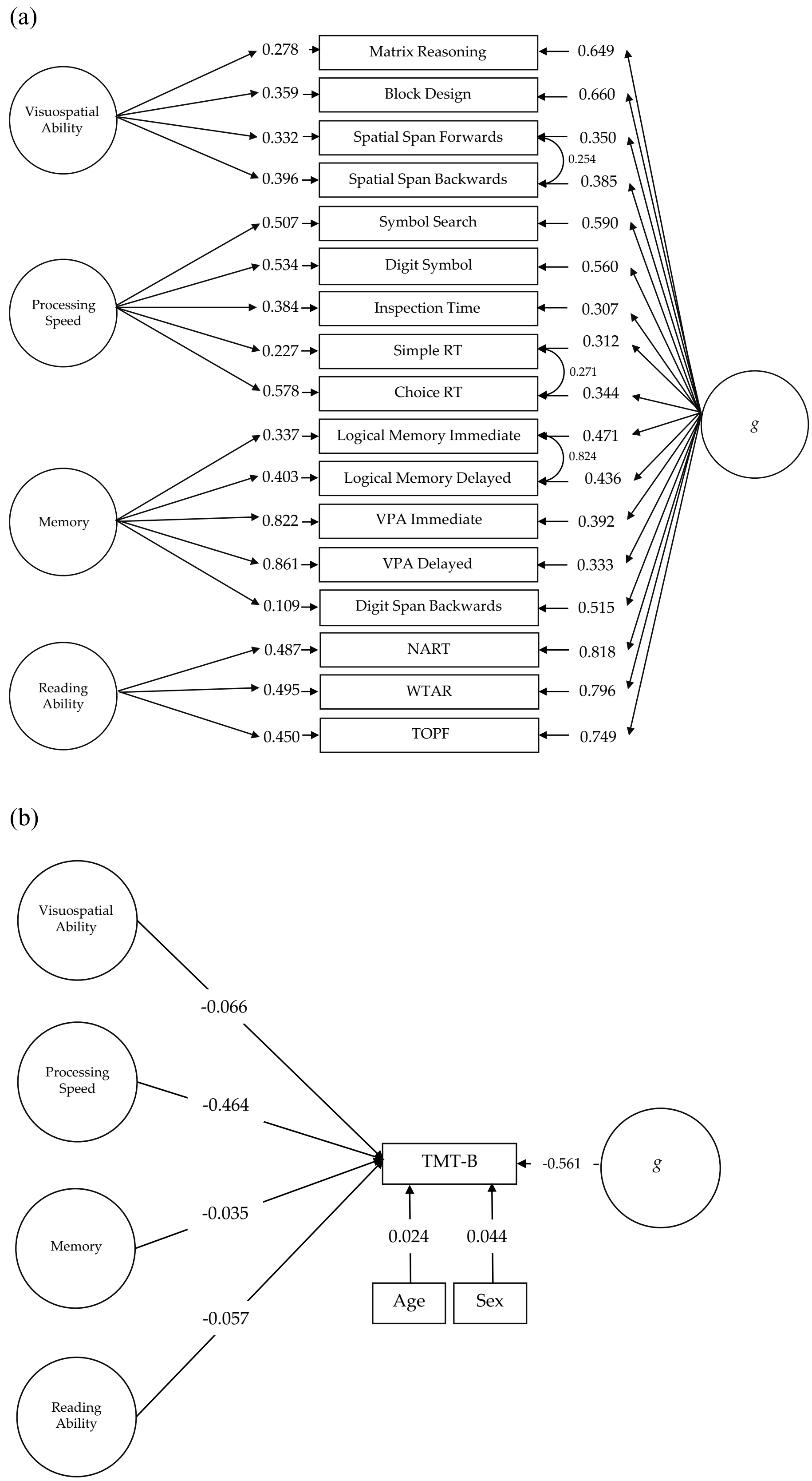

Fig. 3. Measurement and structural aspects of the same bifactor model. (a) The measurement model describes the loadings of cognitive test scores on the cognitive domains; a general factor of intelligence is also derived from the cognitive test scores. (b) The structural aspect of the bifactor model depicts age- and sex-adjusted associations between the cognitive domains (as measured in Fig. 3a) and TMT-B, and age- and sex-adjusted correlations among these domains now that the common variance among tests (*g*) is also modelled. VPA = Verbal Paired Associates; NART = National Adult Reading Test; WTAR = Wechsler Test of Adult Reading; TOPF = Test of Premorbid Functioning; *g* = general factor for intelligence.

variation in TMT-B completion time, over and above the contribution of *g* (i.e., faster processing speed is specifically related to faster TMT-B performance), even among those individuals with the same level of general cognitive ability (*g*). The non-significant associations of visuospatial ability, memory, and reading ability suggest that these latent factors do not contribute anything additional to TMT-B performance

Table 5
Age- and sex-adjusted correlations between the latent factors representing visuospatial ability, processing speed, memory and reading ability in the bifactor model of TMT-B completion times.

	1.	2.	3.	4.
1. Visuospatial ability		0.148	0.189	0.519
2. Processing speed	0.342		0.106	0.245
3. Memory	0.027	0.161		0.164
4. Reading ability	−0.910	−0.374	0.132	

Note: The upper diagonal contains the Pearson correlation coefficients and the lower diagonal contains the corresponding standard errors. Only the association between processing speed and visuospatial was significant (p = 0.021).

Table 6
The factor loadings of each subtest on the general factor.

		Est	SE	p-value
Visuospatial ability	Matrix reasoning	0.649	0.039	< .001
	Block design	0.660	0.049	< .001
	Spatial span forwards	0.350	0.059	< .001
	Spatial span backwards	0.385	0.065	< .001
Processing speed	Symbol search	0.590	0.047	< .001
	Digit symbol	0.560	0.050	< .001
	Inspection time	0.307	0.051	< .001
	Simple RT	0.312	0.043	< .001
	Choice RT	0.344	0.064	< .001
Memory	Logical memory (immediate)	0.471	0.048	< .001
	Logical memory (delayed)	0.436	0.052	< .001
	Verbal paired associates (immediate)	0.392	0.085	< .001
	Verbal paired associates (delayed)	0.333	0.091	< .001
	Digit span backwards	0.515	0.038	< .001
Reading ability	NART	0.818	0.050	< .001
	WTAR	0.796	0.052	< .001
	TOPF	0.749	0.046	< .001

Note: All estimates are fully standardized regression coefficients.

Table 7
Age- and sex-adjusted regression coefficients for the bifactor model of TMT-B completion times measured by visuospatial ability, processing speed, memory, reading ability and a general factor of cognitive ability.

	Est	SE	p-value
Visuospatial ability	−0.066	0.844	0.937
Processing speed	−0.464	0.109	< .001
Memory	−0.035	0.145	0.808
Reading ability	−0.057	0.883	0.948
General factor	−0.561	0.064	< .001

Note: All estimates are fully standardized regression coefficients.

beyond their tests' loading on the general cognitive factor.

4. Discussion

The purpose of the current study was to examine the relationship between TMT-B performance and the cognitive domains of reading ability, visuospatial ability, processing speed, and memory in age-homogeneous older adults. All cognitive tests had moderate to high negative correlations with TMT-B completion times, regardless of the domain they assess, where better performance was associated with faster TMT-B completion times. In the first-order model, where the independent associations of the four cognitive domains with TMT-B were studied, only a significant relationship between TMT-B completion times and the processing speed factor was found, where slower processing speed was associated with slower TMT-B completion times. There was no relationship between TMT-B completion times and the other latent factors. As this first-order model only determines the associations with TMT-B that are driven by specific cognitive abilities, and does not take general cognitive ability into consideration, a bifactor model was then fitted. This model allows for the estimation of a latent general cognitive ability factor based on all cognitive test scores to examine the contribution of *g*, and also the contribution of residual variance that resides in specific cognitive capabilities that is independent of *g*. Higher *g* was a strong contributor to better TMB performance. When the influence of each latent factor was examined beyond the contribution of the general cognitive factor (*g*), again only processing speed independently contributed to TMT-B completion time. The visuospatial ability, memory and reading ability factors were not significant in either model. Most importantly, the results from the bifactor model suggest that, whereas a general factor (*g*) contributes substantially to successful TMT-B performance, there is an additional non-*g* variance contribution from processing speed to TMT-B differences. Again, slower processing speed was associated with slower TMT-B completion times.

The association with processing speed is not surprising given the requirement to switch between number and letters as quickly as possible when performing TMT-B. Previous findings in the literature have also shown that individual differences in speed predict TMT-B performance (Misdraji & Gass, 2010; Oosterman et al., 2010; Sánchez-Cubillo et al., 2009). Salthouse (2011a) also found that a latent speed factor is associated with performance on a TMT-B variant. Previous work has shown that individual differences in processing speed contribute to the relationships between slower TMT-B completion times and thinner frontal, temporal and inferior parietal regions, as well as the integrity of the right uncinate and thalamic radiation, in older adults (MacPherson et al., 2017).

In addition to speed, Salthouse (2011a) also reported that fluid abilities contribute to successful TMT performance on the Connections Test. In our study, after we controlled for a general cognitive factor, using a bifactor model, only speed was associated with TMT-B completion time, and visuospatial ability, reading ability and memory were not. We note that there are several differences between our visuospatial factor and Salthouse's fluid factor, such that our findings cannot be taken as directly contradictory to fluid-TMT associations. Whereas Block Design and Matrix Reasoning are commonly-used fluid indicators, their visuospatial nature combined with the memory elements of the Spatial Span task mean that this factor – though more substantially indicated by Matrix Reasoning and Block Design – might not reflect the same latent cognitive constructs as the fluid factor derived in Salthouse (2011a).

It is important to note that all cognitive domains were associated with TMT-B performance but only the association with *g* and processing speed remained when the first-order and bifactor models were fitted. The lack of association with memory and reading ability in our models is perhaps somewhat surprising given that previous studies have shown that better working memory (Sánchez-Cubillo et al., 2009), episodic memory (Oosterman et al., 2010) and verbal ability (Knight et al., 2006) correlate with better TMT-B performance. These earlier studies used regression analysis with single test scores and did not control for a general cognitive factor before exploring the different cognitive processes that contribute to individual differences on the TMT-B.

It should also be noted that other authors have examined the factor structure of the WAIS subtests (e.g., Benson, Hulac, & Kranzler, 2010; Bowden, Saklofske, & Weiss, 2011; Niileksela, Reynolds, & Kaufman, 2013). However, we based our modelling approach – which includes WAIS subtests alongside other facets of our large cognitive battery – on previously-reported work on the correlational structure of cognitive function in the LBC1936 cohort data (Tucker-Drob et al., 2014). We did make some minor changes. One change was the inclusion of Simple Reaction Time within the speed factor, as it has previously been shown that Simple Reaction Time is closely related to processing speed (Johnson & Deary, 2011). We also included the Test of Premorbid Functioning within our reading ability factor rather than letter fluency.

While the Test of Premorbid Functioning clearly fits in this category of test, letter fluency is likely to require elements of reading and executive function (as illustrated in the current cohort; Hoffman et al., 2017). In any case, despite these minor differences in the variables contributing to our cognitive factors, our data were found to fit the models well.

One limitation of our study is not including a latent factor of executive abilities, given that the TMT-B is an example of a so-called executive test (Delis et al., 2001; Lezak, 1995; Reitan & Wolfson, 1993); yet, there is debate about the degree to which executive functioning and other cognitive domains overlap (Cox et al., 2014; Davis, Pierson, & Finch, 2011; Rabbitt, Lowe, & Shilling, 2001; Salthouse, 2005). Nonetheless, at least 3 variables are required to derive a latent variable and the LBC1936 protocol only includes TMT-B and letter fluency (Deary et al., 2007). Also, whereas the LBC1936 allows access to a large group of healthy older adults, the LBC1936 cohort are a self-selecting group and may typify a somewhat restricted sample (e.g., Johnson, Brett, Calvin, & Deary, 2016). This means that care should be taken when considering these findings in relation to the younger and wider older adult population. Moreover, whereas this model allowed us to partition variance among cognitive tests, which enabled us to test for *g*-independent associations between TMT-B and cognitive domains, it remains moot whether this bifactor structure is a meaningful and biologically-representative model of intelligence. However, testing multiple model specifications to explore other possible accounts of intelligence was beyond the scope of the present study.

The present study's strengths include the large sample size, the narrow age range and demographic homogeneity, which reduces the important confounding effects of age and ethnicity. The LBC1936 cohort allows us the opportunity to examine the shared and independent contributions of performance on different cognitive domains to TMT-B performance, above and beyond the contribution of a general cognitive factor (*g*) in a large sample of older adults. Using a latent variables approach, which reduces specific task influences and measurement error, we highlight the relationship between poorer TMT-B completion times and low *g* and slower processing speed. These findings add to our understanding of the different cognitive abilities that contribute to TMT-B performance and which might be impaired in clinical groups who perform poorly on the TMT-B.

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