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Construct validity of the Trail Making Test: Role of task-switching, working memory, inhibition/interference control, and visuomotor abilities

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Abstract

The aim of this study was to clarify which cognitive mechanisms underlie Trail Making Test (TMT) direct and derived scores. A comprehensive review of the literature on the topic was carried out to clarify which cognitive factors had been related to TMT performance. Following the review, we explored the relative contribution from working memory, inhibition/interference control, task-switching ability, and visuomotor speed to TMT performance. Forty-one healthy old subjects participated in the study and performed a battery of neuropsychological tests including the TMT, the Digit Symbol subtest [Wechsler Adult Intelligence Scale (Third Version) (WAIS-III)], a Finger Tapping Test, the Digits Forward and Backward subtests (WAIS-III), Stroop Test, and a task-switching paradigm inspired in the Wisconsin Card Sorting Test. Correlation and regression analyses were used in order to clarify the joint and unique contributions from different cognitive factors to the prediction of TMT scores. The results suggest that TMT-A requires mainly visuoperceptual abilities, TMT-B reflects primarily working memory and secondarily task-switching ability, while B-A minimizes visuoperceptual and working memory demands, providing a relatively pure indicator of executive control abilities. (*JINS*, 2009, *15*, 438–450.)

Keywords: Ageing, Attentional control, Executive functions, Neuropsychological assessment, Speed of processing, Switch-cost

INTRODUCTION

The Trail Making Test (TMT) is one of the most widely used instruments in neuropsychological assessment as an indicator of speed of cognitive processing and executive functioning (AITB, 1944; Lezak, 1995; Mitrushina et al., 2005; Reitan, 1992; Strauss et al., 2006). The test consists of two parts (A and B). The direct score of each part is represented by the time of completion of the tasks. In addition to direct scores, the B-A difference score, the B:A ratio, and the B-A/A proportional score have been used for clinical proposals as the purest indicators of certain cognitive operations or specific markers of brain damage (but see Periáñez et al., 2007, for a review).

While most studies agree that TMT has a complex and multifactorial structure comprising several cognitive mechanisms, there is a lack of consensus about their exact nature and about their relative contributions to task performance. Table 1 presents an overview of 24 studies that have tried to clarify the processes underlying TMT scores. Visual search, perceptual/motor speed, speed of processing, working memory, and general intelligence are among the most frequently cited constructs thought to contribute to TMT performance. Beyond structural factors such as length of trails or perceptual

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Table 1. Overview of studies with relevance to TMT construct validity

Authors (year)	Sample (N)	TMT scores	Other cognitive scores	Statistical analyses	Results	Conclusions and implications
(1) Groff & Hubble (1981)	Healthy adult women ($n = 40$)	TMT-A, TMT-B	General Aptitude Test Battery (spatial, verbal, numerical, motor, and perceptual abilities)	Factor analysis	TMT-A and TMT-B loaded on a three-factor solution: symbolic fluency (.07 and −.09 factor loadings for parts A and B, respectively), visual perception (−.50 and −.36) and motor (.17 and −.11).	TMT-A and TMT-B require "visual perception" and to a lesser extent, "fine motor abilities." Nonmeasured "attention abilities" are suggested to underlie TMT.
(2) Ehrenstein et al. (1982)	Brain injury patients ($n = 92$) in five groups: Broca and Wernicke aphasics, right and left hemisphere damage, and diffuse injury	TMT-A	Objects Finding Test (OFT), Hidden Patterns Test (HPT), Token Test, Peabody Picture Vocabulary Test, Picture Naming Test	Correlations	Significant correlations between TMT-A and OFT in the five groups of subjects ($r = -.41$, $r = -.93$, $r = -.68$, $r = -.60$, $r = -.70$, respectively) and with HPT only in nonaphasic patients ($r = -.61$, $r = -.58$, $r = -.54$).	TMT-A requires "visual search" abilities.
(3) Corrigan & Hinkeldey (1987)	Brain injury patients ($n = 497$)	TMT-A, TMT-B, B-A, B:A	Impairment Index of Halstead–Reitan Battery, WAIS, WMS	Correlations, factor analysis	All cognitive scores correlated significantly with the four TMT scores	B-A and B:A relate to "intelligence," severity of impairment, and "memory."
(4) Schear & Sato (1989)	Neuropsychiatric male patients ($n = 69$)	TMT-B	Finger Tapping Test, Gr. Pegboard Test, Bausch & Lomb Vision Tester	Correlations, regression	Vision, tapping, and Pegboard correlated with TMT-B ($r = -.27$, $r = -.42$, $r = -.46$, respectively). Tapping speed and Pegboard time together accounted for 29% of TMT-B	"Motor speed" and "dexterity" are important components of TMT-B.
(5) Ricker & Axelrod (1994)	Healthy young and old participants ($n = 58$)	TMT-A, TMT-B	Verbal TMT-A, verbal TMT-B	ANOVA	Results between oral and written performances were comparable across age groups	"Motor and vision factors" are not determinant for TMT-A and TMT-B performance.
(6) Lamberty et al. (1994)	Probable Alzheimer patients ($n = 58$); brain injury patients ($n = 176$); neuropsychiatric patients ($n = 128$); healthy adults ($n = 64$)	TMT-A, TMT-B, B-A, B:A	IQ (measured with WAIS-R)	Correlations	TMT-A, TMT-B, and B-A correlated with IQ (R values between −.37 and −.49) in TBI and neuropsychiatric groups, but B:A did not. No significant correlations between IQ and TMT scores in the Alzheimer's group	B:A ratio captures the essence of "cognitive flexibility" controlling for intrasubject variability factors.
(7) O'Donnell et al. (1994)	Neuropsychiatric patients ($n = 117$)	TMT-B	Category Test, WCST, PASAT, Visual Search and Attention Test (VSAT)	Correlations, PCA	TMT-B correlated over .30 with all cognitive measures. In PCA, TMT-B loaded together with PASAT and VSAT.	TMT-B taps on a "visual scanning/attention."

(*continued*)

Table 1. Continued

Authors (year)	Sample (*N*)	TMT scores	Other cognitive scores	Statistical analyses	Results	Conclusions and implications
(8) Larrabee & Curtiss (1995)	Neuropsychiatric patients ($n = 112$)	TMT-B	WAIS subtests (Information, Vocabulary, Digit Span, Block Design, Object Assembly), Serial Digit (working memory), EPAT (paired associate learning), VSRT (verbal memory), WMS visual reproduction, CFM and CVMT (visual recognition memory), PASAT	Factor analysis	TMT-B loaded together with Block Design, Object Assembly, and visual reproduction	TMT-B is related to "spatial abilities," rather than "attention/immediate memory" or "information processing."
(9) Gaudino et al. (1995)	Undergraduate students ($n = 40$)	TMT-A, TMT-B	TMT-A_{N+L} (TMT-A layout with letters and numbers), TMT-B_N (TMT-B layout with only numbers)	ANOVA	Tasks ordered by average time to complete: TMT-B, TMT-A_{N+L}, TMT-B_N, and TMT-A. All versions differed significantly to each other.	TMT-B reflects an increase of "motor speed," "visual search," and "alternation" demands compared to TMT-A.
(10) Robins Wahlin et al. (1996)	Healthy old adults ($n = 94$)	TMT-A, TMT-B (shortened versions)	MMSE, Block Design Test, Digit Span (DFor, DBack)	Regression	TMT-A: Not predicted by any variable. TMT-B: Marginally predicted by Block Design Test ($\beta = -.152$).	TMT-B relates to "visuospatial skills" but not to "perceptual speed."
(11) Crowe (1998)	Undergraduate students ($n = 98$)	TMT-A, TMT-B	WMS-R span letters and digits (DFor, DBack), WRAT (reading test), TMT-like test with dotted lines connecting empty circles, oral TMT-B, modified TMT without alternating requirements	Correlations, regressions	TMT-A: Predicted by modified TMT ($r^2 = .138$) and TMT-like test ($r^2 = .039$). TMT-B: Predicted by modified TMT ($r^2 = .058$) and oral TMT-B ($r^2 = .053$).	TMT-A reflects "visual search" and "motor speed"; TMT-B reflects "visual search" and "cognitive alternation."
(12) Miner & Ferraro (1998)	Undergraduate students ($n = 110$)	TMT-A, TMT-B	RT task, negative priming task	Correlations, ANOVA	TMT-A: Non-significant correlation with RT task ($r = .15$). TMT-B: No correlation with RT task ($r = .13$) or with negative priming task ($r = .12$).	TMT-B performance is not related to "speed of processing" or "inhibitory functioning."
(13) Arbuthnott & Frank (2000)	Undergraduate students ($n = 34$)	TMT-A, TMT-B, B-A, B:A	Task-switching paradigm (RTs in four different conditions)	Correlations	Significant correlations between attentional set-shifting condition and TMT-B ($r = .36$), B-A ($r = .39$), B:A ($r = .45$). Significant correlation between task-set inhibition condition (once partialed out RTs in non-switch condition) and B:A ($r = .37$).	TMT-B differs from TMT-A in cognitive control, namely "task-set inhibition." B:A is the best TMT "executive" index.

(14) Olivera-Sou za et al. (2000)	Healthy adults ($n = 55$)	TMT-A, TMT-B	Verbal TMT-A, verbal TMT-B, MMSE	Correlations	TMT-A: Low correlation with vTMT-A ($r = -.10$). TMT-B: High correlation with vTMT-B ($r = .59$).	TMT-B and vTMT-B have a common source of variance independently of visual–motor abilities: "set-shifting."
(15) Kowalczyk et al. (2001)	Healthy elderly participants ($n = 60$); dementia patients ($n = 16$)	TMT-A, TMT-B, B-A, B:A	Oral TMT (TMT-A, TMT-B, B-A, and B:A), DigSym, COWAT, efficiency of alphabet, FingT, visual search	Correlations, ANOVA	All TMT scores correlated with their respective oral homologues ($rs > .43$). TMT-A, TMT-B, and B-A scores correlated with Digit Symbol, COWAT, efficiency of alphabet, and finger tapping ($rs > .21$) but not with visual search ($rs < .18$). B:A only correlated with Digit Symbol ($r = -.40$) and COWAT ($r = .25$).	TMT-B is influenced by "cognitive flexibility" and "psychomotor ability." B:A diminishes the influence of psychomotor demands.
(16) Spikman et al. (2001)	TBI patients ($n = 60$); healthy young and old controls ($n = 60$)	TMT-A, TMT-B	SCW, RT Distraction Task, PASAT-5, RT Dual Task, 15 Words Test (LOC score), MCST (PERSREL score)	PCA	"Memory-driven Action" component defined by SCW, PASAT-5, TMT-B, LOC score, and PERSREL (reflecting control processes). "Stimulus-driven Reaction" component, defined by RT Dual task and RT Distraction task (speed of reaction).	Not related to TMT validity.
(17) Kortte et al. (2002)	Veterans Affairs Medical Center outpatients ($n = 121$)	TMT-A, TMT-B	WCST scores (% Pers. Err. and FMS), CVLT, COWAT, Digit Span (WAIS-R)	Correlations, regressions	TMT-A: Correlated with all measures except WCST FMS. TMT-B: Correlated with all measures except WCST FMS and was predicted by WCST % Pers. Err., once the influence of age and TMT-A was controlled (R^2 change = .07).	TMT-B differs from TMT-A in "cognitive flexibility."
(18) Ríos et al. (2004)	TBI patients ($n = 29$); healthy controls ($n = 30$)	TMT-A, TMT-B, B:A	WCST (Pers. Err, Pers. Resp, Incorrect Resp, Correct Resp, Non-Pers. Err); SC, SW, SCW	PCA	TMT-A: Loaded in a speed factor together with SC, SW, and SCW. TMT-B: Loaded in a speed factor together with SC, SW except with SCW and WCST Non-Pers. Err, and in a cognitive flexibility factor together with Pers. Err, Pers. Resp, Incorrect Resp, and Correct Resp. B:A: Loaded in both cognitive flexibility and working memory factors.	TMT-A taps on "speed of processing." TMT-B taps on "speed of processing" and "cognitive flexibility" factors. B:A taps on both "cognitive flexibility" and "working memory" factors but not on "speed of processing."

(*continued*)

Table 1. Continued

Authors (year)	Sample (N)	TMT scores	Other cognitive scores	Statistical analyses	Results	Conclusions and implications
(19) Royan et al. (2004)	Healthy adults ($n = 60$)	TMT-A, TMT-B	Math test, Symbol Digit Modality Test, Digit Span (DFor, DBack), Adjusting-PSAT	Correlations, regressions	TMT-A: Predicted by Adjusting-PSAT (speed of processing; $r = .33$). TMT-B: Predicted by math test ($r = -.41$), SDMT ($r = -.39$), and highly with Adjusting-PSAT ($r = .60$).	Not related to TMT validity.
(20) González-Blanch et al. (2006)	First-episode schizophrenia patients ($n = 131$)	TMT-A, TMT-B	DFor and DBack, Cancellation Task, CPT, DigSym, Rey figure, Rey word list. COWAT, Brief Att. Test, Gr. Pegboard, FingT, WAIS III Verbal Compr. Index	PCA	TMT-A (.68) and TMT-B (.59) loaded in a executive functions/speed of processing factor, along with Digit Backward (.53), Digit Symbol (.58), and Cancellation task (.83).	TMT-A and TMT-B are nonspecific measures of “speed of processing” and “executive functioning.”
(21) Chaytor et al. (2006)	Neurological adult patients ($n = 46$)	TMT-A, TMT-B, B-A	WCST % Pers. Err, SCW, SInt, COWAT	Correlations	Both TMT-B and B-A correlated with Stroop CW ($r = .55$, $r = .49$), COWAT ($r = .38$, $r = .32$) and WCST % Pers. Err ($r = .34$, $r = .32$).	Not related to TMT validity.
(22) Jefferson et al. (2006)	Healthy old adults ($n = 222$); mild cognitive impairment (MCI: $n = 166$)	TMT-B	MMSE, COWAT, BNT, Animal Naming	Correlations	Controls: TMT-B correlated with MMSE ($r = -.27$), COWAT ($r = -.31$), BNT ($r = -.23$), and Animal Naming ($r = -.31$). MCI: TMT-B correlated with MMSE ($r = -.4$), COWAT ($r = -.33$), and BNT ($r = -.41$).	Not related to TMT validity.
(23) Mahurin et al. (2006)	Schizophrenia patients ($n = 84$)	TMT-A, TMT-B	MCST, Digit Cancellation Test, DigSym, Token Test, Verbal Series Attention Test	Correlations, regressions	TMT-A: Predicted by Digit Cancellation. TMT-B: Predicted by Digit Cancellation and Verbal Series Errors.	TMT-A reflects “visual search,” while TMT-B reflects “visual search” and “mental tracking.”
(24) Langenecker et al. (2007)	Healthy young participants ($n = 63$)	TMT-A, TMT-B	Parametric Go/No-Go Test (eight scores)	Correlations	TMT-A: Correlated with RT to targets in the Go/No-Go task ($r = .34$). TMT-B: Correlated with percentage of correct target trials ($r = -.38$) and with percent of inhibition trials ($r = -.39$) in the complex executive version of the Go/No-Go task.	TMT-A reflects “sustained attention” and “set maintenance,” while TMT-B adds “response inhibition” and “set shifting.”

Note. Direct (TMT-A and TMT-B) and derived TMT scores (B-A and B:A), WAIS-R (Wechsler Adult Intelligence Test-Revised), WMS-R (Wechsler Memory Scale-Revised), DigSym (WAIS-III Digit Symbol), FingT (finger tapping), DFor (WAIS-III Digit Forward), DBack (WAIS-III Digit Backward), SC (Stroop Color), SW (Stroop Word), SCW (Stroop Color-Word), SInt (Stroop Interference score), SwitchC (Switch Cost in WCST-like task = RT switch – RT repeat), BNT (Boston Naming Test), MMSE (Mini Mental State Examination), MCST (Modified Card Sorting Test), COWAT (Controlled Word Association Test), CVLT (California Verbal Learning Test), PASAT (Paced Auditory Serial Addition Test), CPT (Continuous Performance Test), SDMT (Symbol Digit Modality Test), PCA (principal components analysis), and ANOVA (analysis of variance).

complexity, the TMT-B has been proposed to involve additional "executive function" demands (Lezak, 1995; Mitrushina et al., 2005; Strauss et al., 2006). Cognitive alternation/flexibility, inhibition/interference control, working memory, mental tracking, and attentional set-shifting are some of the most frequently reported constructs accounting for the increased times in TMT-B performance (Table 1). However, both the lack of consensus regarding the terminology used to refer to cognitive constructs and the discrepancies regarding the involvement of some of these abilities in TMT make it difficult to clarify what does the TMT ultimately measure. In order to disentangle these confounding factors, it is useful to review which basic processes have been associated with TMT performance and how have they been operationalized.

Working memory has been related to both parts A and B in several studies (Crowe, 1998; Larrabee & Curtiss, 1995; Mahurin et al., 2006). For instance, Kortte et al. (2002) found that neither TMT-A nor TMT-B part was related to maintaining information in working memory as measured by Failures to Maintain Set on the Wisconsin Card Sorting Test (WCST). On the contrary, only the ability to alternate between different memory sets (manipulation) measured by means of Percent Perseverative Errors of the WCST significantly predicted TMT-B performance. Accordingly, the key factor mediating TMT and working memory seems not to rely merely on storage but on central executive components of memory (Baddeley, 1986). The consistent finding across studies of a significant correlation between TMT-B and WCST perseverative indices supports the idea that cognitive flexibility, also referred to as "attentional set-shifting" or "task-set switching," could capture key executive abilities underlying part B performance (Chaytor et al., 2006; Kortte et al., 2002; Lamberty et al., 1994; Langenecker et al., 2007; O'Donnell et al., 1994; Ríos et al., 2004; Spikman et al., 2001). For instance, Arbuthnott and Frank (2000) directly addressed the relationship between TMT scores and a supposedly pure measure of cognitive flexibility, that is, the behavioral switch-cost as measured in task-switching paradigms (see a recent review in Monsell, 2005). Their analysis of reaction time (RT) costs revealed a specific association between B:A and the ability to inhibit *versus* alternate between task-sets. However, the absence of any other cognitive measures besides their task-switching paradigm made it difficult to disentangle the specific contribution of switching ability beside alternative cognitive abilities previously related to TMT. To our knowledge, no other reports have attempted to examine the relationship between TMT and behavioral switch-costs. In accordance to Arbuthnott and Frank (2000), a relationship between TMT-B and inhibitory abilities has been supported on the basis of significant correlations between TMT and the Stroop Interference condition (Chaytor et al., 2006; Spikman et al., 2001). However, the use of more specific measures of inhibitory abilities such as Go/No-Go tasks (Langenecker et al., 2007) or negative priming tasks (Miner & Ferraro, 1998) has provided contradictory evidence about the role of inhibition in TMT scores with both positive and negative results, respectively. Last, the general assumption that both TMT-A and TMT-B involve visuomotor factors has been questioned based on results from an oral version of the TMT (Kowalczyk et al., 2001; Olivera-Souza et al., 2000; Ricker & Axelrod, 1994). Indeed, the high compatibility demonstrated between oral and written TMT versions puts into question the role of these factors given that the oral TMT eliminates visual and motor demands. Moreover, the lack of correlation between TMT scores and an RT task further questioned the relationship between TMT and motor speed factors (Miner & Ferraro, 1998).

Across studies, at least three different sources of variability may be held responsible for the inconsistencies described above. First, most TMT validation studies have considered between two and four cognitive measures only. Just 9 of the 24 studies reviewed in Table 1 included neuropsychological batteries containing five or more variables. Given the wide range of cognitive abilities related to TMT performance (i.e., perceptual, motor, attentional, memory, or inhibition abilities), validation studies that consider only a small number of variables may produce a biased interpretation of the mechanisms underlying TMT performance. A second potential source of variability and discrepancy between studies is related to sample composition. Thus, samples from 10 of the reviewed studies were exclusively constituted by healthy participants and only 2 of them included old adults. Of the 14 remaining studies, 5 included neuropsychiatric patients, 3 included neurological patients, and the 6 remaining studies included a mixture of healthy and neurological or psychiatric samples. On the one hand, the use of clinical groups has been shown to hide particular dangers. It has been reported that using clinical groups for TMT validation purposes, even those with mild neurological impairment, may bias the findings as patients may be using compensatory strategies to complete the test (Jefferson et al., 2006; Spikman et al., 2001). In fact, the pattern of correlations and factorial loadings between TMT and other cognitive measures has shown changes between different clinical samples even within studies (Lamberty et al., 1994). Thus, the use of clinical groups may be biasing validation results by overstating compensatory cognitive factors and understating impaired abilities. On the other hand, the extended use of young and middle-age healthy samples may limit the potential generalization of validity results to different samples outside this age range where TMT has proved to be a sensitive indicator of cognitive disabilities (Periáñez et al., 2007). Third, the use of different statistical methodologies between studies may also contribute to apparent differences in the results. As reviewed in Table 1, correlation coefficients were calculated in 16 studies: 7 used factor analysis, 5 used regression analysis, and 4 used analyses of variance. However, only eight of all studies included more than one statistical method, thus limiting the comparisons among studies.

The present study aims to examine the cognitive processes underlying TMT performance while sorting out some limitations from prior investigations. The specific objective was to clarify the relative contribution from working memory, inhibition/interference control, task-switching ability, and visuomotor speed to both direct and derived TMT scores (Table 1). To our knowledge, no previous work has comprehensively explored the joint and individual contributions of all these factors to both direct and derived TMT indices. We assessed a sample of healthy old adults, thus maximizing the potential generalization of results to adult populations and reducing the risks derived from using clinical samples for validation purposes, as detailed above.

MATERIALS AND METHODS

Participants

A sample of 41 Spanish Caucasian healthy old adults (mean ± *SD* age = 59.4 ± 6.9 years; range = 49–78 years; mean ± *SD* years of education = 11.4 ±3.6; 12 males) took part in this study. Participants were recruited as volunteers from special university courses for retired and elderly people, university staff, and health care centers. A self-reported history of medical and psychiatric problems was obtained from each participant. History of neurological disease, psychiatric illness, head injury, stroke, substance abuse (excluding nicotine), learning disabilities, and any other difficulty that may interfere with testing were the exclusion criteria. All participants had normal or corrected-to-normal vision. Subjects exhibited no signs of cognitive impairment and scored higher than 26 in the Mini Mental State Examination (Folstein et al., 1975) (mean ± *SD* = 29.2 ±1.1; range = 26–30). In addition, subjects scored within normal ranges in the standardized neuropsychological tests used, according to Spanish published norms: TMT (Periáñez et al., 2007), Wechsler Adult Intelligence Scale (Third Version) (WAIS-III) subtests (Wechsler, 1999), and Stroop Test (Golden, 1994).

Instruments and Procedure

Neuropsychological examination was conducted by experienced psychologists in two different sessions: (1) an initial interview and a standardized neuropsychological testing and (2) a computerized testing using a task-switching paradigm. This study was completed in compliance with institutional research standards for human research and in accordance with the Declaration of Helsinki.

Trail Making Test

Participants were administered parts A and B of the TMT according to the guidelines presented by Strauss et al. (2006). Total time in seconds for parts A and B was recorded, representing the TMT-A and TMT-B direct scores. Three derived scores were also calculated: difference score (B-A), ratio score (B:A), and Log B:A. The logarithmic transformation of B:A score aimed to reduce the potential impact of dispersion in scores and may be useful to generalize results across healthy and clinical groups. The proportional score (B-A/A) was not considered for analyses due to its linear dependency with B:A, as indicated elsewhere (Periáñez et al., 2007).

Digit Symbol subtest (WAIS-III)

Speed of perceptual processing and visual search were assessed using the Digit Symbol subtest from the Spanish adaptation of the WAIS-III (Wechsler, 1999). The number of symbols correctly encoded in 2 min was considered as the dependent variable for analyses.

Finger Tapping Test

The Finger Tapping Test is thought to measure self-directed manual motor speed. According to the guidelines presented by Strauss et al. (2006), subjects were instructed to tap as rapidly as possible using the index finger. The number of taps done in five trials of 10-s duration was recorded for each hand. The average number of taps was the dependent variable for analyses.

Digits Forward and Backward subtests (WAIS-III)

These subtests from the Spanish adaptation of the WAIS-III (Wechsler, 1999) were used in order to assess working memory and mental tracking processes. Both direct scores were recorded separately and included in the analyses as the dependent variables for analyses.

Stroop Test

The Spanish adaptation of the Stroop Test (Golden, 1994) was used to assess the ability to maintain a goal in mind and to inhibit a habitual response in favor of a less familiar one (inhibitory/interference control). The number of correct responses in 45 s in the Color-Word condition was recorded as the dependent variable. Errors were indicated by the examiner, and participants were asked to correct them before continuing.

Task-switching paradigm

Task-switching ability was measured by means of a modified version of a classical test of executive function, the WCST (Barceló et al., 2000, 2002; Periáñez et al., 2004). This WCST modification has generated reliable switch-cost effects (Barceló et al., 2000, 2002, 2006; Periáñez et al., 2004). The behavioral switch-cost in RTs is thought to reflect the time consumed by an executive control mechanism necessary to switch from one task to another (Monsell, 2005). In addition, WCST behavioral switch-cost met some criteria established to distinguish between top-down control and task execution processes during task-switching (Meiran, 1996; Monsell, 2005): RT switch-cost (1) was specific of task-switch trials (Barceló et al., 2002, 2006), (2) did not diminish over successive task blocks (could not be automatized with practice; Barceló et al., 2002), and (3) was reduced by increasing preparation intervals between switch cues and target events (consistent with the notion that executive control may occur in advance of task performance; Periáñez & Barceló, 2009). At the neuroanatomical level, WCST behavioral switch-costs have revealed association with a frontoparietal network (Barceló et al., 2002, 2006; Periáñez et al., 2004). Consistent with current neuroanatomical models of cognitive control (Koechlin & Summerfield, 2007; Miller & Cohen, 2001), this network involved the sequential activation of the inferior frontal gyrus, anterior cingulate cortex, and supramarginal gyrus (Periáñez et al., 2004). Taken together, both behavioral and neuroimaging data are consistent with the existing task-switching literature and support that WCST switch-costs reflect executive control rather than task-specific processes.

The task was run using a PC with a 14-inch monitor, which was controlled by Presentation software (http://www.neurobs.com). Subjects were instructed to switch between color and shape sorting rules on the basis of a trial-by-trial task-cueing procedure. Sorting rules were cued 2000 ms prior to the target display by means of two different tones (500 or 2000 Hz at 65 dB; Figure 1). The target display remained on screen until the participant selected a response by means of a four-button panel (using the index and middle fingers of each hand) in an array corresponding to the layout of the four key cards. After each response, a feedback text appeared on the computer screen during 200 ms indicating "right," "wrong," "too fast," or "too slow" performance (response time limit of 3 s). Following prior guideline reports, the overall probability of shift and repeat trials was set to 25 and 75%, respectively, in order to minimize task-set reconfiguration processes prior to switch trials (Monsell, 2005). The task-switching experimental session lasted around 30 min including a 10-min training period. RTs were measured in both switch and repeat trials. A switch-cost score was calculated for each participant according to standard procedures (Monsell, 2005) by subtracting mean RTs in correct repeat trials from mean RTs in correct switch trials (RT switch-cost = RT switch − RT repeat). Subjects performed the task in two blocks with 216 target cards per block.

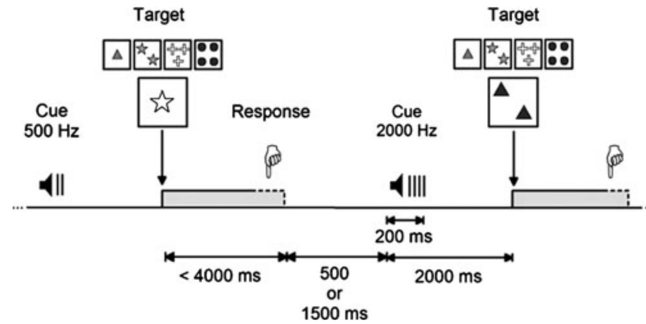

Fig. 1. Task-switching protocol. The sequence of events during task-switching performance started with a tonal cue instructing subjects to switch or to repeat the classification rule used in the immediately preceding trial (i.e., color or shape classifications). The switch/repeat meaning of the two tones (500 and 2000 Hz, 65dB) was counterbalanced between subjects. After each tonal cue, a choice card appears centered on the screen together with the four key cards on top and remained on display until a response was given. Responses were immediately followed by "correct," "incorrect," "too fast," and "too slow" feedback text written on the screen (200-ms duration).

Data Analyses

Shapiro–Wilk's test was used to assess normality in the distribution of the variables as a prerequisite for regression analyses (Table 2). Repeated measures Student's *t* test comparing mean RTs during task-switch *versus* task-repeat trials from the task-switching paradigm helped to decide whether there was a significant switch-cost. Given the relatively small sample size, which may represent a limit for analyses based in correlational methodologies, a set of exploratory correlation analyses helped to reduce the initial set of selected variables and to decide which of them should be included in regression models of TMT scores. The predictive value of variables that correlated significantly with TMT scores was explored using simple and multiple linear regression analyses, thus clarifying their independent and unique contributions to predict each TMT score. Last, the same multiple linear regression analyses were performed using age as a covariate in order to remove its influence from the analyses and explore the potential

Table 2. Descriptive statistics and S-W tests of normality

	TMT scores					Other cognitive measures					
	TMT-A	TMT-B	B-A	B:A	Log B:A	DigSym	FingT	DFor	DBack	SCW	SwitchC
N	41	41	41	41	41	41	41	41	41	41	41
Mean	37.9	77.6	39.7	2.1	0.3	57.3	60.5	8.1	5.8	37	52.5
SD	13.6	29.2	21.5	0.6	0.1	13.9	6.7	1.9	1.7	7.7	107.4
Minimum–maximum	21–77	35–188	13–113	1.2–4.1	0.1–0.6	32–90	43.6–75.5	5–13	2–10	22–53	−232.3–236.7
Skewness	1.4	4.3	3.1	3.9	0.8	−0.20	0.06	−0.17	0.30	−0.28	0.06
S-W	$1.09^{\text{n.s.}}$	$0.81^{\text{n.s.}}$	$0.83^{\text{n.s.}}$	$0.98^{\text{n.s.}}$	$0.63^{\text{n.s.}}$	$0.42^{\text{n.s.}}$	$0.46^{\text{n.s.}}$	$1.02^{\text{n.s.}}$	$0.88^{\text{n.s.}}$	$0.86^{\text{n.s.}}$	$0.70^{\text{n.s.}}$

Note. Direct (TMT-A and TMT-B) and derived TMT scores (B-A, B:A, and Log B:A), DigSym (WAIS-III Digit Symbol), FingT (finger tapping), DFor (WAIS-III Digit Forward), DBack (WAIS-III Digit Backward), SCW (Stroop Color-Word), SwitchC (RT Switch Cost in WCST-like task = RT switch − RT repeat), S-W (Shapiro–Wilk test of normality), and n.s. (nonsignificant differences, two-tailed).

generalization of results to samples out of this age range. Our interpretation of results relied on these regression models, where the number of variables analyzed never exceeded the recommended ratio of 10 subjects per variable (Tabachnick & Fidell, 2007). *A priori* (planned) contrasts were used in all statistical comparisons with an uncorrected significance level of $p < .05$ given that our variable selection derived from an extended review of studies already demonstrating relationship between scores. SPSS v.14.0 statistical software package was used to perform analyses.

RESULTS

Descriptive statistics of all scores, including TMT direct and derived scores, are shown in Table 2. All variables were normally distributed.

Task-Switching Paradigm

Accuracy was high, with an average percentage of correct trials of 90.4% ($SD = 0.98$). Repeated measures Student's t test revealed a significant switch-cost effect of 52 ms (switch *vs.* repeat trials; $t_{40} = 3.1$; $p < .003$).

Exploratory Correlation Analyses

Intercorrelation Pearson coefficients between TMT scores and other cognitive measures are shown in Table 3. The analyses of correlations between direct and derived scores revealed that only B-A was modestly related to TMT-A. In contrast, all derived scores correlated significantly with TMT-B (Table 3). TMT-A scores correlated with Digit Symbol, Digit Backward, and Stroop Color-Word scores. TMT -B scores correlated with Digit Symbol, Digit Backward, Switch-cost, and Stroop Color-Word scores. While the B-A derived score correlated with Digit Symbol, Digit Backward, Switch-cost, and Stroop Color-Word, both B:A and Log B:A did not show significant correlations with any other cognitive measure.

Regression Analyses

Digit Symbol, Digit Backward, and Stroop Color-Word accounted for 40, 24.8, and 11.3% of the variance of TMT-A when considered independently of each other, as revealed by simple linear regression models. The multiple regression model including the same variables was significant ($R^2 = .45$, $p < .0001$) and revealed that only Digit Symbol had a significant unique contribution of 17.14% to the prediction of TMT-A (Table 4, top panel). The same multiple regression model using age as a covariate replicated the pattern of results ($R^2 = .35$, $p < .001$) with Digit Symbol as the unique variable significantly contributing to the prediction of TMT-A (11.22%, $p < .02$).

Digit Symbol, Digit Backward, Switch-costs, and Stroop Color-Word accounted for 32.3, 28.9, 11.2, and 14.6% of the variance of TMT-B when considered independently of each other. The multiple regression model including the same variables was significant ($R^2 = .48$, $p < .0001$) and revealed that both Digit Backward and Switch-costs had significant unique contributions of 9.4 and 6.9%, respectively, to the prediction of TMT-B (Table 4, middle panel). The same multiple regression model using age as a covariate ($R^2 = .39$, $p < .001$) replicated the pattern of results with Digit Backward and Switch-costs having unique contributions of 9.9 and 5.2% to the prediction of TMT-B. However, the contribution of Switch-costs to this model was just marginal ($p < .03$ and $p = .09$ for Digit Backward and Switch-costs, respectively).

Digit Symbol, Digit Backward, Switch-costs, and Stroop Color-Word accounted for 13.9, 17.4, 10.1, and 9.4% of the variance of B-A, respectively, when considered independently of each other. The multiple regression model including the

Table 3. Correlation matrix

	DigSym	FingT	DFor	DBack	SCW	SwitchC	TMT-A	TMT-B	B-A	B:A	Log B:A
DigSym											
FingT	.19										
DFor	.28	−.03									
DBack	.48**	.23	.47**								
SCW	.48**	−.01	.11	.34*							
SwitchC	−.21	−.07	−.16	−.03	.04						
TMT-A	−.63**	−.01	−.23	−.50**	−.34*	.22					
TMT-B	−.57**	−.14	−.27	−.54**	−.38*	.33*	.73**				
B-A	−.37*	−.18	−.22	−.42*	−.31*	.32*	.36*	.90**			
B:A	.09	−.11	.04	−.11	−.15	.11	−.29	.39*	.71**		
Log B:A	.08	−.12	−.00	−.11	−.12	.13	−.31	.40*	.73**	.98**	

Note. Direct (TMT-A and TMT-B) and derived TMT scores (B-A, B:A, and Log B:A), DigSym (WAIS-III Digit Symbol), FingT (finger tapping), DFor (WAIS-III Digit Forward), DBack (WAIS-III Digit Backward), SCW (Stroop Color-Word), and SwitchC (RT Switch Cost in WCST-like task = RT switch − RT repeat).
*$p < .05$ (two-tailed).
**$p < .01$.

Table 4. Results of multiple regression analysis on TMT-A, TMT-B, and B-A scores

	B	*SE* (*B*)	*β*	*t*	*p*	Partial	Semipartial
TMT-A							
DigSym	−0.502	0.148	−.509	−3.392	.002	−.487	−.414
DBack	−2.045	1.122	−.255	−1.822	.077	−.287	−.222
SCW	−0.006	0.249	−.003	−0.025	.981	−.004	−.003
TMT-B							
DigSym	−0.579	0.323	−.272	−1.790	.082	−.286	−.214
DBack	−6.092	2.371	−.353	−2.569	.014	−.394	−.307
SwitchC	0.074	0.034	.273	2.203	.034	.345	.263
SCW	−0.534	0.530	−.140	−1.007	.321	−.165	−.120
B-A							
DigSym	−0.112	0.276	−.072	−0.405	.688	−.067	−.056
DBack	−3.990	2.024	−.314	−1.971	.056	−.312	−.273
SwitchC	0.060	0.029	.301	2.093	.043	.329	.290
SCW	−0.494	0.453	−.177	−1.091	.283	−.179	−.151

Note. Direct and derived TMT scores (TMT-A, TMT-B, and B-A), DigSym (WAIS-III Digit Symbol), DBack (WAIS-III Digit Backward), SwitchC (RT Switch Cost in WCST-like task = RT switch − RT repeat), and SCW (Stroop Color-Word).

same variables was significant ($R^2 = .3$, $p < .001$) and revealed that only Switch-costs had a significant unique contribution of 8.41% to the prediction of B-A difference score (Table 4, lower panel). The same multiple regression model using age as a covariate ($R^2 = .26$, $p < .02$) replicated the pattern of results with Switch-costs being the best predictor of B-A (7.5%, $p = .06$), which was closely followed by Digit Backward (7.3%, $p = .07$).

DISCUSSION

The aim of this study was to clarify which cognitive mechanisms underlie TMT direct and derived scores. A sample of 41 healthy individuals was assessed by means of a battery of neuropsychological measures that, according to a comprehensive review of the literature, had previously demonstrated a relationship with TMT performance.

A series of exploratory Pearson product-moment correlations confirmed the relationship between TMT-A and TMT-B direct scores ($r = .73$), supporting the general assumption of common cognitive factors modulating both scores. As shown in Table 3, results also confirmed our *a priori* assumption about a relationship between TMT scores and most cognitive scores selected for the analyses. The cognitive measures that were significantly correlated with TMT scores were entered in a series of regression models to assess their joint and unique contributions as predictors of TMT scores (TMT-A, TMT-B, and B-A).

Multiple regression analysis performed on TMT-A explained 45% of the variance and suggested that this score was primarily affected by speed of visual search (as measured by WAIS-III Digit Symbol score). These results agree with several previous studies, suggesting that visual search and perceptual speed are better candidates to account for a substantial amount of variance in TMT-A (Table 1) as compared to motor speed factors (e.g., Ricker & Axelrod, 1994). This result contradicts a previous work using a Finger Tapping Task in a neuropsychiatric sample (Schear & Sato, 1989). Nevertheless, the well-known presence of motor deficits in these patients may introduce a confound factor, overestimating the role of motor factors (Rodríguez-Sánchez et al., 2008). Digit Backward and Stroop Color-Word accounted individually for 24.3 and 11.3% of TMT-A, as reflected by simple regression analysis. However, their relevance in the prediction of part A disappeared when all predictor variables were jointly considered in a multiple regression analysis. The current finding clarifies a previous misunderstanding and suggests that the relationship between TMT-A and both Stroop and Digit Backward scores vanishes after controlling for visual search and perceptual speed factors, as suggested elsewhere (Rapport et al., 1994; Ríos et al., 2004).

Multiple regression analysis performed on TMT-B accounted for 48% of the variance, with Digit Backward and Switch-cost as the main contributing factors. The ability to manipulate information in working memory (as measured by WAIS-III Digit Backward score) explained the greater portion of TMT-B variance compared to the other variables, even when speed of visual search factors were controlled for (as measured by Digit Symbol). This finding is in accordance with Crowe (1998), who suggested that working memory could explain more variance of TMT-B than alternation factors (i.e., task-switching). Furthermore, our results also confirm the broad assumption that task-switching ability is one critical cognitive mechanism differentiating TMT-A and TMT-B (Arbuthnott & Frank, 2000; Ríos et al., 2004). Taken together, these findings may help conciliating apparent discrepancies regarding the role of working memory *versus* task-switching in TMT performance. Indeed, the effective implementation of executive control mechanisms, for example, switching between two tasks, may necessarily rely on the activation of short-term representations in working memory (Baddeley, 1986; Norman & Shallice, 1986). Last, and as found in TMT-A analyses, the individual contribution of Stroop Color-Word (14.6%) to the prediction of TMT-B in the simple regression analysis disappeared in the multiple regression analysis. Again, this result can be interpreted as produced by shared perceptual speed factors (Ríos et al., 2004). Therefore, task-switching seems to be more appropriate than the inhibition/interference control (measured by Stroop Color-Word) as the candidate mechanism that differentiates performance of TMT-B *versus* TMT-A (see Miner & Ferraro, 1998, for analogous evidences).

Multiple regression analysis performed on B-A difference scores accounted for 30% of the variance, with Switch-cost as the main contributing variable. This was followed by working memory that, however, did not reach statistical significance (Table 4). According to the assumption that behavioral switch-costs represent a relatively pure indicator of cognitive control and executive functioning (Monsell, 2005), our results suggest that B-A was the best TMT index of executive functioning. This finding partially contradicts preceding TMT validation studies, where task-switching ability was best related to B:A and not to B-A score (Arbuthnott & Frank, 2000). However, key differences between the task-switching paradigm used by Arbuthnott and Frank (2000) and the one used in this study may account for this discrepancy.[a] First, the use of three task-sets in Arbuthnott and Frank's (2000) experiment, as compared with the two task-sets used here has shown to increase behavioral Switch-costs due to increasing working memory demands and minimizing task-switching abilities (Barceló et al., 2006; Langenecker et al., 2007; Mitrushina et al., 2005). Second, increasing the overall probability of task-switch trials to 60% of the trials, like in Arbuthnott and Frank's (2000) study, has demonstrated to almost suppress behavioral switch-costs (Monsell & Mizon, 2006). Thus, when the expectation of a task switch is high within a task, subjects may begin to prepare for switching in advance of task-switch trials, that is, during task-repeat trials, which would result in a subestimation of task-switching ability. In sum, the use of an experimental paradigm with a low memory load (two task-sets) and a low portion of task-switch trials (25%), like the one used here, may provide a more reliable indicator of task-switching ability while minimizing working memory demands and avoiding subjects to strategically/probabilistically prepare for task-switching in anticipation of a task-switch trial.

As noted earlier, none of the additional cognitive scores considered correlated with B:A or with Log B:A. This lack of correlation is consistent with previous studies (Corrigan & Hinkeldey, 1987). Alternatively, the B:A score could be indexing cognitive factors different than those considered in the present work. Further investigation including sustained attention (Ríos et al., 2004) and verbal abilities (Kortte et al., 2002) should clarify whether these cognitive factors may alternatively account for B:A score.

In conclusion, our results are clear, suggesting that TMT-A requires mainly visuoperceptual abilities, TMT-B primarily reflects working memory and secondarily task-switching ability, while B-A minimizes visuoperceptual and working memory demands, providing a relatively pure indicator of executive control abilities. The present results on TMT validity will help the clinician to interpret altered patient scores in terms of a failure of the cognitive mechanisms detailed here. However, caution must be taken when trying to generalize the present results to clinical populations since patients may be using compensatory strategies to complete the test (Jefferson et al., 2006; Spikman et al., 2001). Regression results were overall replicated when the influence of age was removed from multiple regression models by covariance analysis, providing preliminary evidence about the likely generalizability of results to younger samples. However, future works using larger samples in a wide age range should further support these findings.

[a] In the experiment by Arbuthnott and Frank (2000), subjects were told to switch between three alternative task-sets (i.e., A, B, C). The experiment was structured in sequences of five trials (i.e., AABCB). Switch trials involved switching to another task (A**AB**CB), switching to the remaining task (AA**BC**B), or returning to the previous task (AAB**CB**). Each of the four blocks performed consisted in 30 trials (six sequences of five trials), yielding a total of 18 switches every 30 trials. Moreover, two of every three series began with a switch condition, meaning at least three intersequence switches per block and therefore 21 switches per block. Accordingly, their overall probability of switch trials was 60%.

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