



Published in final edited form as:

Clin Neuropsychol. 2017 January ; 31(1): 154–167. doi:10.1080/13854046.2016.1238510.

Multicomponent analysis of a digital Trail Making Test

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Abstract

Objective—The purpose of the current study was to use a newly developed digital tablet-based variant of the TMT to isolate component cognitive processes underlying TMT performance.

Method—Similar to the paper-based trail making test, this digital variant consists of two conditions, Part A and Part B. However, this digital version automatically collects additional data to create component subtest scores to isolate cognitive abilities. Specifically, in addition to the total time to completion and number of errors, the digital Trail Making Test (dTMT) records several unique components including the number of pauses, pause duration, lifts, lift duration, time inside each circle, and time between circles. Participants were community-dwelling older adults who completed a neuropsychological evaluation including measures of processing speed, inhibitory control, visual working memory/sequencing, and set-switching. The abilities underlying TMT performance were assessed through regression analyses of component scores from the dTMT with traditional neuropsychological measures.

Results—Results revealed significant correlations between paper and digital variants of Part A ($r_s = .541, p < .001$) and paper and digital versions of Part B ($r_s = .799, p < .001$). Regression analyses with traditional neuropsychological measures revealed that Part A components were best predicted by speeded processing, while inhibitory control and visual/spatial sequencing were predictors of specific components of Part B. Exploratory analyses revealed that specific dTMT-B components were associated with a performance-based medication management task.

Conclusions—Taken together, these results elucidate specific cognitive abilities underlying TMT performance, as well as the utility of isolating digital components.

Keywords

Trail Making Test; executive functions; speed; medication management; inhibition

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Disclosure statement

No potential conflict of interest was reported by the authors.

Introduction

Trail Making Tests are commonly used in neuropsychological assessments, in part because they are sensitive to a variety of neurological disorders. The original version comprises two conditions, Part A and Part B (TMT-A, TMT-B; Army Individual Test Battery, 1944; Reitan, 1992). In Part A, the participant is instructed to draw a line connecting 26 encircled numbers in ordered sequence (1–2–3 ... 26) as quickly as possible. In Part B, the participant is to connect a series of 26 circles containing either a number or letter in alternating sequence (1–A–2–B ... 13). Conditions are scored on the total time to completion and number of errors committed. Both conditions of the test have been used under the assumption that they are measuring overlapping but also different cognitive processes. TMT-A is considered to primarily measure visual search speed and tracking. Studies that have examined the cognitive abilities required in TMT-A have found that Part A is predicted largely by visual search/processing speed (e.g. Ríos, Periañez, & Muñoz-Céspedes, 2004; Sánchez-Cubillo et al., 2009). In contrast, TMT-B has been associated with processing speed and more complex cognitive abilities (Arbuthnott & Frank, 2000; Korte, Horner, & Windham, 2002; Strauss, Sherman, & Spreen, 2006). However, the specific aspects of TMT-B that make it more cognitively demanding remain relatively unclear. In this study, we use a digital version of the TMT to identify and isolate specific cognitive abilities involved in trail making performance.

It has been proposed that performance on TMT-B is related to cognitive flexibility in that correctly alternating between numbers and letters requires simultaneously sequencing two series and switching between sets of information (Strauss et al., 2006). Several studies have found TMT-B to be correlated with the Wisconsin Card Sorting Test perseverative errors (Chaytor, Schmitter-Edgecombe, & Burr, 2006; Korte et al., 2002; Lamberty, Putnam, Chatel, Bieliauskas, & Adams, 1994; Langenecker, Zubieta, Young, Akil, & Nielson, 2007; O'donnell, Macgregor, Dabrowski, Oestreicher, & Romero, 1994; Ríos et al., 2004; Spikman, Kiers, Deelman, & van Zomeren, 2001), which provides evidence for Part B as an index of executive control and set-shifting ability. In other work, TMT-B performance was predicted by WAIS-III Digit Span-Backwards and a task-switching measure (Sánchez-Cubillo et al., 2009). These studies suggest that in addition to visual search and processing speed, TMT-B performance requires working memory/sequencing (Sánchez-Cubillo et al., 2009) and set-switching (Arbuthnott & Frank, 2000; Sánchez-Cubillo et al., 2009). Conceptually, inhibiting the overlearned response to continue the sequence of only numbers or only letters without alternating appears integral to TMT-B performance, and there is some evidence to suggest this (Arbuthnott & Frank, 2000). However, the contribution of inhibitory control to TMT-B performance remains largely unclear. Inhibitory control in TMT-B may represent the speed at which set-switching occurs and may in part explain the inconsistency in association of TMT-B with other cognitive measures of response inhibition. Given the multiple aspects of cognitive ability TMT-B requires, it is not particularly surprising that it is sensitive to neurological dysfunction. Yet, because multiple domains of ability are involved, the particular cognitive skills that contribute to TMT-B performance are not clear, and may vary among individuals. Therefore, deconstructing TMT performance may help to identify clinically relevant cognitive processes.

Several alternate versions of the TMT have been developed to better isolate the nature of cognitive difficulties on the TMT. Some trail making variants are structurally similar to the original version, but include more conditions (Delis, Kaplan, & Kramer, 2001), while others are structurally different (Salthouse et al., 2000). For example, in the Delis-Kaplan Trail Making Test (Delis et al., 2001) performance (i.e. time to completion) can be compared across five conditions in order to identify more diffuse or specific (e.g. motor speed) cognitive difficulties. Researchers have also developed and utilized derived scores in an attempt to better isolate cognitive processes associated with TMT-B performance (Lamberty et al., 1994; Lange, Iverson, Zakrzewski, Ethel-King, & Franzen, 2005; Salthouse, 2011). The three most common methods are subtracting total time to complete TMT-A from total time to complete TMT-B (B–A); the ratio of B to A (B:A), or the residual of TMT-B after it has been regressed on Part A (BrA; Fellows, Byrd, & Morgello, 2014; Fellows & Schmitter-Edgecombe, 2015; Salthouse, 2011). In a principal components analysis, the BrA derived score loaded on the same component as CLOX (Royall, Cordes, & Polk, 1998) and the Behavioral Assessment of the Dysexecutive Syndrome Zoo map subtest (Wilson, Alderman, Burgess, Emslie, & Evans, 1996), which provides further support for this index as a measure of more complex executive functions (Fellows & Schmitter-Edgecombe, 2015). Conceptually, these methods reduce the shared variance between conditions, therefore isolating executive functioning aspects of TMT-B. However, evidence has suggested that other variables may contribute to differences in performance between conditions. For example, the total distance to complete TMT-B is longer than TMT-A, which leads to longer time to completion and presents issues regarding the validity of derived scores (Gaudino, Geisler, & Squires, 1995). The longer total distance of TMT-B compared to TMT-A may also add an additional level of difficulty to TMT-B performance (Franzen, Paul, & Iverson, 1996; Gaudino et al., 1995).

Computerized cognitive assessments have the potential to utilize the structure of existing test constructs while capturing additional information. Although there are digital variants of the trail making test (Poreh, Miller, Dines, & Levin, 2012; Zakzanis, Mraz, & Graham, 2005), they do not all maximize aspects of precise and automatic data collection. However, there is some evidence that computerized TMTs can provide useful information regarding the individual cognitive abilities involved in trail making performance (Salthouse & Fristoe, 1995). For example, one investigation of a computerized TMT found that specific age-related effects associated with distinct components (e.g. median time before and on target circle, number of keystrokes, median time for movement in the same direction vs. different direction) of the task were primarily due to the speed at which task components were executed (Salthouse & Fristoe, 1995). Further, another study that utilized a computerized TMT analyzed performance on five equally divided subsections (i.e. Section 1: circles 1–5; Section 2: circles 6–10, etc.) of the task and found that performance on the last section of TMT-B, but not other sections, correlated with phonemic fluency ability and a switching index score (Poreh et al., 2012). Although these studies have demonstrated the utility of digital trails variants, they have not explored the potential of using more recent technological developments.

The TMT, particularly Part B, has shown to be one of the most consistent predictors of functional abilities in healthy older adults, mild cognitive impairment, and neurological

populations. For example, a recent meta-analysis found that across multiple cognitive domains and neuropsychological measures, TMT-B accounted for the largest amount of variance in functional status in mild cognitive impairment (McAlister, Schmitter-Edgecombe, & Lamb, 2016). TMT-B has also been found to be a predictor of medication management ability in Parkinson's disease (Manning et al., 2012), and instrumental activities of daily living in community-dwelling older adults (Bell-McGinty, Podell, Franzen, Baird, & Williams, 2002; Cahn-Weiner, Boyle, & Malloy, 2002). Despite the sensitivity of TMT-B to everyday functioning, the cognitive processes underlying the association remains unclear. For example, two patients may both obtain the same score on the TMT-B, but for different reasons. One patient may perform poorly because of difficulties with visuospatial sequencing, while the other may experience difficulties with inhibitory control. Conceptually, the potential variability in mechanisms underlying performance would have different implications for projecting functional outcomes and treatment planning. Therefore, deconstructing TMT component processes may elucidate the specific abilities underlying performance in order to more clearly characterize cognitive deficits and subsequent contributions to functional impairment, while retaining its robust predictive power.

The purpose of the current study was to identify cognitive abilities underlying TMT performance in a mixed sample of neurologic and healthy older adults. To identify and isolate specific cognitive abilities assessed in TMT performance, including processing speed, visual working memory/sequencing, inhibitory control, and set-switching, a tablet-based version of the TMT was created that allowed for collection of several embedded component measures. Similar to the original version, this tablet-based test comprises two conditions, Part A and Part B. Both parts are structurally similar to the original version. Rather than adding conditions to isolate performance subcomponents, this version is designed to isolate separate components of each condition using automated algorithms. We hypothesized that information processing speed would be the primary ability associated with performance on digital TMT-A component measures, whereas sequencing, switching, and inhibition ability would account for a larger proportion of variance in TMT-B component measures. We were especially interested in whether the digital component measures of TMT-B (e.g. pauses, time inside circle) would be able to capture aspects of performance associated with specific cognitive abilities (e.g. set-switching) and medication management skills.

Methods

Participants and procedure

Participants were 81 community-dwelling older adults between the ages of 50 and 93 (see Table 1). Participants were recruited through advertisements, health and wellness fairs, physician referrals, and prior studies in our laboratory. The Telephone Interview for Cognitive Status (TICS; Brandt & Folstein, 2003) was used as a brief estimate of cognitive ability. Additionally, the Wechsler Test of Adult Reading (WTAR; Wechsler, 2001) was administered to provide an estimate of premorbid ability. Inclusion criteria for the current study consisted of being age 50 years or older and ability to provide informed consent.

Participants were excluded from the current study if they were unable to complete either trial of the digital Trail Making Test (dTMT; $n = 2$).

Two sets of participants were selected for inclusion into the current study. The first set of 68 participants comprised both healthy older adults ($n = 31$) and individuals with neurologic/neuropsychiatric diagnoses, including Parkinson's disease (PD; $n = 10$), mild cognitive impairment (MCI; $n = 13$), and other conditions with known cognitive effects ($n = 14$). The 'other' category included participants with self-reported conditions (e.g. mild traumatic brain injury, multiple sclerosis, bipolar disorder) with known cognitive effects. Participants were not excluded based on chronic medical conditions common among older adults (e.g. hypertension, thyroid disease, etc.). Parkinson's disease was diagnosed by a board certified neurologist with specialization in movement disorders. Classification of MCI was established through consensus between two neuropsychologists using established criteria (Albert et al., 2011). These criteria included self or informant report of subjective memory impairment for at least six months, scoring at least 1.5 standard deviations below age-matched norms or relative to prior testing on a measure in one or more cognitive domains (i.e. memory, language, executive functioning, and/or speeded processing), generally preserved functional abilities, and not meeting DSM-IV criteria for dementia (American Psychiatric Association, 2000). Of note, the dTMT was not used in the diagnostic classification. Although no formal performance validity tests were administered as part of this study, this set of participants was administered the Memory Assessment Scale 12-item forced choice recognition test (Williams, 1991). Of the 67 participants who completed this test, the minimum correctly recalled items was 10 out of 12, and 92.5% of participants correctly recalled all 12 items. As such, we consider this to be indicative of adequate effort.

The second set of participants included only neurologically healthy community-dwelling older adults ($n = 13$). This subset of participants was comparable to the total sample in age ($M = 62$, $SD = 8.3$) and years of education ($M = 15.6$, $SD = 2.4$). These participants completed both the digital and paper versions of the TMT, but not the other cognitive measures administered in this study. These participants were included to increase the sample size for analyses comparing TMT versions, however, they received a different battery of cognitive tests. All participants were compensated for travel, as applicable, and were provided with a brief report of their performance on standardized tests administered. The Institutional Review Board at Washington State University approved this research protocol and all participants provided informed consent.

The first set of participants completed a neuropsychological assessment which included the following tests: paper-based Trail Making Test (pTMT; Reitan, 1992), dTMT, written version of the Symbol Digit Modalities Test (SDMT; Smith, 1991), Wechsler Memory Scale-Third Edition (WMS-III) Spatial Span (Wechsler, 1997), as well as the Delis-Kaplan Executive Functioning System Color-Word Interference Test (CWIT) and Design Fluency (DF) Condition 3 (Delis et al., 2001). For both sets of participants, the dTMT was administered approximately 60 min after the paper-based version. Of note, the order of dTMT and pTMT was not counter-balanced because practice effects could potentially interfere with the data of the larger studies that added the dTMT. Participants also completed the performance-based Medication Management Ability Assessment after both the pTMT

and the dTMT were administered. Details of the measures used in this study and the constructs they were used to represent are presented below. These tests were selected from a larger battery of tests used in an ongoing study of cognitive and functional abilities in older adults.

Neuropsychological tests

Symbol Digit Modalities Test (SDMT; Smith, 1991)—Participants are instructed to match a series of symbols to the corresponding number in the key at the top of the page. The total number of correct responses in 90 s was used as a measure of speeded processing.

Wechsler Memory Scale – Third Edition Spatial Span (WMS-III SS; Wechsler, 1997)—Participants are instructed to touch blocks in either the same order (Trial 1) or the reverse order (Trial 2) that the examiner touches. The total number of correct responses on both trials was used as a measure of visual working memory/sequencing.

DKEFS Color-Word Interference Test (CWIT; Delis et al., 2001)—The Color-Word Interference Test (CWIT) test is a variant of the Stroop procedure and consists of four conditions. The total number of correct responses in Condition 3 (Inhibition) was used as a measure of inhibitory control.

DKEFS Design Fluency (DF; Delis et al., 2001)—In this task a piece of paper with rows of boxes is presented, each with several dots inside. The participant is instructed to draw a design in as many boxes as possible in one minute using four straight lines without repeating any designs. The total number of correct designs drawn in Condition 3 (Switching) of this test was used as a measure of switching ability.

Trail Making Test – Paper Version (pTMT; Reitan, 1992)—In Part A of the TMT, participants are instructed to sequentially connect 26 encircled numbers in ascending order (i.e. 1–2–3 ...). In Part B, the participant connects 26 circles alternating between numbers and letters (i.e. 1–A–2–B ...). Time to complete each part was recorded.

Trail Making Test – Digital Version (dTMT)—Regarding the administration of the dTMT, the tablet was placed flat on the table in front of the participant who was read the same set of instructions as those used for the paper version (Strauss et al., 2006), with the exception of replacing ‘pencil’ for ‘stylus’ and ‘page’ for ‘screen.’ The dTMT is an Android-based app that was created to automatically extract participant performance features, and details of development can be found in Dahmen, Cook, Fellows, and Schmitter-Edgecombe (2016). While these include automatically calculated measures of number of errors and time to completion, the dTMT also uses timestamps provided by the tablet hardware to output the time the user spends drawing between and inside circles. Timing begins as soon as the stylus makes contact with the tablet screen and stops as soon as the last circle is touched. If the wrong circle is entered a red X is presented over the circle and the administrator informs the participant that a circle was skipped and to return to the last correct circle. Although the layout of the dTMT is similar to the paper-based version, the dTMT only has 20 circles in Part A and 19 in Part B, rather than 26. Given that the tablet

screen is smaller (10.1" × 6.9") than a normal 8.5" × 11" piece of paper, the number of circles was reduced so that the tablet screen was not too crowded and to reduce the difference in total distance between Part A and B. To maintain stimuli visibility, particularly for use in assessing older adults and neurologic populations, we decided to reduce the number of circles, rather than the size of the circles. The length of dTMT-A is 109.23 cm and dTMT-B is 116.35 cm, a difference in length of 7.12 cm, which is considerably less than the 56.9 cm difference between Part A and B of the paper-based TMT (Gaudino et al., 1995). While a similar layout to the paper-based TMT is utilized, several new digital features were developed. These other measures of performance captured by the dTMT include: number of pauses, average pause duration, number of lifts, average lift duration, time inside each circle, and time between circles. These components were developed to further elucidate and isolate the cognitive abilities associated with TMT performance. Upon completion, a screenshot of the test is automatically exported to a file along with annotations that mark the location of pauses and lifts. This file can be reviewed to evaluate the clinical relevance of pause and lift location. A detailed description of each additional digital feature is given below. Of note, each of the components was extracted separately for TMT-A and TMT-B.

Pauses—A pause is recorded if the stylus remains in the same location on the tablet screen for longer than 0.1 s. Given the sensitivity of the tablet to movement, the ‘same location’ is defined to be a point less than 10 pixels in any direction from the original touch down point. Both the number and duration of pauses is recorded.

Time inside circle—The ‘time inside circle’ component is the number of milliseconds that the stylus is inside a circle. This time interval ends when the stylus exits the circle.

Lifts—When the stylus is removed from the surface of the tablet screen a lift is automatically recorded by the app. The lift ends when the user touches the surface of the tablet screen. Both the number of lifts and the amount of time the stylus is off the tablet screen is recorded.

Time between circles—The total time outside of the circles was automatically recorded by the app. The time starts after the first circle is exited and stops when each subsequent circle is entered.

Functional measure

Medication Management Ability Assessment (MMAA; Patterson et al., 2002)—

In this performance-based test of medication management ability participants are provided with detailed instructions regarding the way a medication regimen should be taken. The details include correct dosage, time of day administered, and whether the medication should be taken with food. After a time-delay, participants are given four medication bottles with simulated medications (i.e. different colored beans) and instructed to correctly arrange the pills based on the provided instructions. The test is scored on the correct dosage taken each time, the number of times per day each dosage is taken, and the total number of correct dosages per day. The total score for this measure was used for analysis in the current study.

Statistical analyses

Correlation analyses were conducted to establish concordance between the paper and digital versions of the TMTs. Spearman's rho (r_s) correlation analyses were conducted for non-normally distributed data. The magnitude of agreement between TMT versions was considered in the context of conventional use of effect size guidelines for measuring correlations for a similar construct as low 0.0–0.3, moderate 0.4–0.5, and moderate to high 0.6–0.8. To determine whether the digital TMT component measures were associated with specific cognitive abilities, dTMT total time to completion, number of pauses, average pause duration, number of lifts, average lift duration, average time between circles, and average time inside circles were regressed on the cognitive domain measures (i.e. SDMT, CWIT-Inhibition, Design Fluency-Switching, and Spatial Span Total). To examine the extent to which specific aspects of dTMT performance relate to functional outcomes, exploratory regression analyses were conducted regressing dTMT components on medication management skills (i.e. Medication Management Ability Assessment).

Results

Participant characteristics are presented in Table 1. The sample was comprised of mostly well-educated, right-handed, non-Hispanic white females with above average estimated verbal intellectual ability. In the full sample ($n = 81$), the dTMT-A total time showed a significant and moderate correlation with Part A of the paper version of the TMT ($r_s = .530$, $p < .001$) and dTMT-B total time showed a significant and high correlation with the paper TMT-B ($r_s = .795$, $p < .001$). Age was associated with dTMT-A ($r_s = .286$, $p = .010$), pTMT-A ($r_s = .340$, $p = .002$), dTMT-B ($r_s = .442$, $p < .001$), and pTMT-B ($r_s = .426$, $p < .001$). Neither dTMT nor pTMT performance were associated with years of education (p 's $> .15$).

To determine whether digital component measures of the dTMT (e.g. pauses, time inside circle) could capture aspects of performance associated with the different neuropsychological measures, regression analyses were conducted ($n = 63$ – 65). Given that age showed a significant correlation with the dTMT it was initially entered as a covariate in the regression equations. Adding age as a covariate did not change the general pattern or significance of results for any of the analyses. Therefore, to reduce the number of predictors in the equation, age was not included as a covariate in the final analyses. Correlations between the predictor and outcome variables are shown in Table 2. Multicollinearity for the models was inspected and was within an acceptable range (all VIFs < 2). As seen in Table 3, for the dTMT-A regression models total time, pauses, time between circles, and time inside circles were all significant, R^2 s $\geq .20$. Information processing speed, measured by the SDMT, was the only predictor to account for significant variance in each of the significant dTMT-A models (t s > 2.08). The dTMT-A models for pause duration, number of lifts, and lift duration were not significant (F s < 2.00).

In contrast, all of the dTMT-B models were significant (see Table 3). For dTMT-B total time to completion, CWIT-Inhibition ($t = 2.87$) and Spatial Span ($t = -2.19$) emerged as the only significant predictors ($R^2 = .524$). CWIT-Inhibition was the only significant predictor of number of pauses ($t = 2.50$), pause duration ($t = 3.08$), and time between circles ($t = 3.84$). Spatial Span emerged as the only significant predictor of lift duration ($t = -3.56$) and

average time inside circles ($t = -2.57$). Spatial Span ($t = -2.55$) and the SDMT ($t = -2.46$) predicted the number of lifts. These results suggest that processing speed is being captured by the digital components of dTMT-A measuring pauses and aspects of time (e.g. total time and time within and between circles). No significant neuropsychological predictors were found for dTMT-A for number of lifts or lift duration. In contrast, for dTMT-B, inhibition predicted the TMT-B digital components measuring number of pauses, pause duration, and time between circles. Working memory predicted number of lifts, lift durations, and time inside circle.

Two exploratory regression analyses were conducted to examine the contribution of dTMT-B component processes to medication management. Because entering all six dTMT-B components resulted in issues with multicollinearity as well as with number of predictors for the sample size, two separate analyses were conducted. In the first analysis ($n = 57$) the three dTMT-B components that were only associated with inhibitory control (i.e. CWIT-I) were entered as predictors of MMAA performance. These three predictors were number of pauses, pause duration, and time between circles. In the second exploratory regression analysis ($n = 59$), the remaining three predictors that were more related to spatial working memory (i.e. Spatial Span) were entered as predictors. The first model accounted for 17.3% of the variance in MMAA performance, $F(3, 53) = 3.71, p = .017$. dTMT-B average pause duration emerged as the only significant component predictor of MMAA performance, $\beta = -.38, t(57) = -3.03, p = .029$. Neither the average time between circles ($\beta = -.23, p = .179$), nor the number of pauses ($\beta = -.29, p = .086$) were significant predictors of MMAA performance. The second model, with dTMT-B number of lifts, lift duration, and average time inside circles accounted for 20.2% of the variance in MMAA performance $F(3, 55) = 4.65, p = .006$. The average time inside circles ($\beta = -.67, p < .001$) and average lift duration ($\beta = .46, p = .009$) were significant predictors. The total number of lifts was not a significant predictor in the model ($\beta = .13, p = .306$). Between the two models, dTMT-B average pause duration, average time inside circles, and average lift duration were significant predictors of performance on a standardized medication management task.

An additional regression analysis with the dTMT-A components that were associated with the SDMT in the previous analyses was conducted to examine the role of speeded processing in MMAA performance. The four dTMT-A components that were used as predictors were number of pauses, average pause duration, average time inside circles, and average time between circles. Multicollinearity was inspected and deemed to be in an acceptable range (i.e. VIFs 1.7–2.3). The overall model was not significant, $F(4, 52) = 1.67, R^2 = .114, p = .170$.

Discussion

The primary aim of this study was to better characterize cognitive processes underlying TMT performance by examining cognitive abilities associated with embedded component measures calculated using the dTMT in a mixed sample of neurologic and healthy older adults. The results revealed moderate to high correlation between the dTMT and the paper-based version. Twenty percent of the variance in total time to complete dTMT-A was accounted for by the neuropsychological tests, with the perceptual/motor speed measure (i.e.

SDMT) as the only predictor accounting for a significant amount of the variance. Perceptual/motor speed as measured with the SDMT was also the only significant predictor of the digital TMT-A components. Specifically, the number of pauses, time between circles, and time inside circles were all predicted by the SDMT. This finding is consistent with previous research that has identified perceptual speed as the primary ability being assessed with TMT-A (Salthouse, 2011; Sánchez-Cubillo et al., 2009).

In contrast, approximately 52% of the variance in dTMT-B time to completion was predicted, with significant independent contributions of inhibition (i.e. CWIT-Inhibition) and visual working memory (i.e. Spatial Span). This pattern of results supports the notion that TMT-B involves more complex cognitive processes, than TMT-A, and is consistent with prior research that has found that working memory and task switching ability are involved in TMT-B performance (Sánchez-Cubillo et al., 2009). Interestingly, the switching condition of Design Fluency was not a significant predictor in any of the models. Moreover, prior research has shown that the switching trial of Design Fluency shows a higher correlation with the Visual Scanning trial of the DKEFS TMT, than residual Number-Letter Switching trial performance (Suchy, Kraybill, & Gidley Larson, 2010). Therefore, future research may benefit from examining the relation of the TMT with other measures that may more thoroughly assess switching ability.

Even though participants are instructed not to lift the stylus from the tablet when completing the TMT, this occurs regularly in both the digital and paper-based version. Per standard administration of this test, the examiner reminds the participant not to lift the stylus from the screen prior to completing the task. Although lifts are not recorded as an error, these lifts may be useful for understanding the processes involved in trail making performance. In this study, speed and spatial sequencing accounted for a significant proportion of the variance in dTMT-B lifts, such that more lifts were associated with longer time to completion and lower sequencing ability. Of note, lift duration and time inside circles were not associated with speed, but were inversely related to visual sequencing ability such that poorer sequencing was associated with longer lift duration and time inside circles. It may be that individuals with a lower visual working memory capacity are more likely to lift the stylus off the screen for a longer duration and spend more time in circles in order to search and recall the correct sequence of circles. The larger proportion of time inside circle variance accounted for by visual working memory in dTMT-B compared to dTMT-A is consistent with the notion that Part B is more demanding on sequencing resources, which may simultaneously affect the rate at which this information is processed. As such, lift duration and average time inside circles may be clinically useful indices of how visual working memory ability may impact TMT performance. In future research it may also be useful to examine lifts in relation to measures of motor control.

The dTMT-B used in the current study was designed to retain the predictive power of the paper version, while simultaneously collecting additional clinically relevant component processes. Derived scores (e.g. B/A ratio) developed to better characterize executive functions have been shown to be associated with task-set inhibition (Arbuthnott & Frank, 2000). However, as previously noted, the longer total distance of paper TMT-B makes it a more cognitively demanding task, compared to Part A (Franzen et al., 1996; Gaudino et al.,

1995) and therefore complicates interpretation of derived scores. An advantage to the dTMT in the current study is that executive control processes can be isolated without reliance on TMT-A performance. For example, dTMT-B number of pauses, pause duration, and time between circles were only predicted by the inhibitory control measure (i.e. CWIT-Inhibition). This finding suggests that these components may be useful for isolating inhibitory control from other cognitive processes involved in trail making performance. Conceptually, hesitation during this task, as measured by both number and duration of pauses, may reflect greater difficulty inhibiting incorrect trail connections.

Although TMT-B performance is often associated with functional abilities (McAlister, Schmitter-Edgecombe, & Lamb, 2016), the specific cognitive skills that contribute to medication management are unclear. In the current study, dTMT-B average pause duration, average time inside circles, and average lift duration were the only significant predictor of performance on a medication management task. Notably, the neuropsychological measures of inhibitory control (i.e. CWIT-I) and spatial working memory (i.e. Spatial Span), but not speeded processing, were the only significant predictors of dTMT-B pause duration, time inside circles, and average lift duration. These results provide preliminary evidence of dTMT-B components to isolate aspects of executive control and working memory that contribute to functional abilities and could be clinically useful. Moreover, the dTMT-A components that were associated with the SDMT did not predict MMAA performance, which further suggests that speeded processing may not be a significant contributor to medication management ability as measured by the MMAA. However, given the small sample size and exploratory nature of these analyses, more research is needed to confirm the utility of these components.

The initial findings from this study provide additional understanding of the cognitive abilities underlying TMT performance, but several limitations must be considered. First, the participants in the current study were mostly Caucasian females with high levels of education, which limits the ability to generalize the findings to the general population. Correlation analyses revealed that both dTMT and pTMT performance were associated with age, but not years of education. It is possible that years of education is less relevant to TMT performance among individuals with higher levels of education. Moreover, the small sample size of this preliminary study precluded conducting separate analyses to examine whether the dTMT measures the same underlying constructs in both neurologic and healthy older adults. Future research with a larger number of neurologically healthy older adults and individuals with a specific neurological condition is needed to determine the consistency of the constructs underlying dTMT performance. Electronic device familiarity was not formally assessed in this study so it was not possible to systematically examine the potential contributions to performance. Another limitation is that test administration was not counterbalanced between the digital and paper variants of the test; the paper version was always administered before the digital version. The tests were not counterbalanced because the digital version was added to the neuropsychological battery in the context of a larger study that required consistency in data collection over time. More research with a larger sample, counterbalanced administration, and test-retest reliability is needed. A larger sample will also allow for more complex algorithms to be applied to the data, which may increase diagnostic sensitivity and specificity.

In summary, these results suggest that dTMT components may be able to isolate cognitive processes believed to be important in TMT performance. Although TMT-A and its components appear to require primarily visual-scanning/psychomotor processing speed, TMT-B components involved more complex visual sequencing and inhibitory control. The data further suggest some specificity to the cognitive processes associated with the dTMT-B components. More specifically, inhibitory processes predicted the dTMT-B components measuring number of pauses, pause duration and time between circles, and working memory predicted the dTMT-B components measuring number of lifts, lift durations and time inside circle. Examining differential performance on dTMT components may help identify particular reasons for poor performance on the TMT (e.g. speed vs. inhibitory control), which could be useful for increasing specificity in diagnosis and treatment planning. However, the goal of the current study was to examine whether the dTMT could identify component cognitive processes underlying TMT performance, not to evaluate diagnostic sensitivity or specificity. More research is needed in larger healthy and neurological samples to further elucidate the clinical utility, discriminant validity, and test–retest reliability of the dTMT.

Acknowledgments

Funding

This work was supported by the NIH: National Institute of Biomedical Imaging and Bioengineering (NBIB) Smart Environment Technologies for Health Assessment and Assistance [grant number R01 EB009675] and the National Science Foundation [grant number DGE-0900781].

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Table 1Participant characteristics ($n = 81$).

	Mean (SD) or %
Age	67.1 (9.2)
Education	16.1 (2.5)
Sex (% Female)	74.1
<i>Race-ethnicity (%)</i>	
Non-Hispanic White	93.8
Non-Hispanic Black	1.2
Non-Hispanic Asian	2.5
Other/not reported	2.5
Handedness (% Right)	95.1
TICS	34.6 (3.1)
WTAR	111.8 (10.6)

Note: TICS = Telephone Interview of Cognitive Status ($n = 79$); WTAR = Wechsler Test of Adult Reading.

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Table 2

Digital Trail Making Test component correlations.

	SDMT	DF-S	CWIT-I	SS
<i>Part A</i>				
Time	-.451	-.221	.362	-.205
# Lifts	-.133	-.049	.136	-.102
Lift Dura	.001	.001	.080	-.052
# Pauses	-.525	-.337	.406	-.219
Pause Dura	-.336	-.102	.223	-.054
Between	-.419	-.219	.252	-.105
Inside	-.433	-.209	.380	-.151
<i>Part B</i>				
Time	-.576	-.595	.625	-.524
# Lifts	-.347	-.240	.386	-.322
Lift Dura	-.229	.173	.296	-.309
# Pauses	-.503	-.533	.527	-.433
Pause Dura	-.256	-.374	.417	-.202
Between	-.340	-.419	.368	-.268
Inside	-.526	-.548	.568	-.425

Notes: Bolded values are statistically significant at $p < .01$. SDMT = Symbol Digit Modalities Test; DF-S = Design Fluency- Switching; CWIT-I = Color-Word Interference Test-Inhibition; SS = Spatial Span. $n = 64-68$.

Table 3

Regression analyses of digital Trail Making Test components and NP scores.

dTMT-A							
Variables	Time	Pauses	Pause d	Lifts	Lift d	Between	Inside
SDMT	-.37*	-.30*	-.37*	-.26	.14	-.29*	-.40**
DF-S	-.07	-.19	.05	.00	.17	-.06	-.16
CWIT-I	.07	.10	.00	-.17	.05	.13	-.08
SS	-.03	.11	.05	-.19	-.24	-.02	.07
<i>F</i>	3.82	3.63	1.98	1.57	.85	3.13	5.25
<i>R</i> ²	.20**	.20*	.11	.19	.05	.18*	.26**
dTMT-B							
SDMT	-.20	-.14	.02	-.32*	.02	.13	-.23
DF-S	-.06	-.20	-.15	.07	.19	-.00	-.06
CWIT-I	.39**	.34*	.45**	.07	.11	.53***	.24
SS	-.26*	-.04	.08	-.34*	-.50**	-.15	-.31*
<i>F</i>	16.10	8.02	4.84	6.32	4.12	6.61	10.93
<i>R</i> ²	.52***	.36***	.25**	.29***	.21**	.31***	.43***

Notes: β - values are presented, unless otherwise noted.

SDMT = Symbol Digit Modalities Test; DF-S = Design Fluency-Switching; CWIT-I = Color-Word Interference Test-Inhibition; SS = Spatial Span. *n* = 63-65.

* *p* < .05;

** *p* < .01;

*** *p* < .001.