Neurocognitive Correlates of the Trail Making Test for Older Children in Patients with Traumatic Brain Injury

Nicholas S. Thaler1, Daniel N. Allen1,*, Jacqueline S. Hart1, James R. Boucher1, Janice C. McMurray1, Joan Mayfield2

1Department of Psychology, University of Nevada Las Vegas, Las Vegas, NV, USA
2Our Children’s House at Baylor, Dallas, TX, USA

*Corresponding author at: Department of Psychology, University of Nevada, Las Vegas, 4505 S. Maryland Parkway MS 5030, Las Vegas, NV 89073-5030, USA. Tel.: 702-895-0121; fax: 702-895-0195.
E-mail address: daniel.allen@unlv.edu (D.N. Allen).

Accepted 15 March 2012

Abstract

Studies have found that processing speed and working memory influence performance on the Trail Making Test (TMT), though little research is available in this regard for the TMT for Children (TMT-C), particularly in clinical populations. The purpose of the present study was to examine cognitive mechanisms that are thought to underlie performance on the TMT-C in a sample of children who sustained traumatic brain injury. Sixty-one children and adolescents with moderate to severe brain injuries completed the TMT-C and performed a battery of neuropsychological tests. Regression analysis was used to analyze the relationship between cognitive constructs and TMT-C performance. Results indicated that processing speed predicted Trails A performance while backwards span tasks predicted Trails B performance. These findings corroborate with previous studies and provide evidence of the mechanisms that underlie TMT-C performance in brain injured children.

Keywords: Assessment; Childhood brain insult; Childhood neurologic disorders; Intelligence; Statistical methods; Learning and Memory

Introduction

The Trail Making Test for older children (TMT-C; Reitan & Wolfson, 1992) is a shortened version of the original TMT (Army Individual Test Battery, 1944) consisting of two parts (A and B), each of which contains 15 targets rather than the original 25 targets on the adult version. Although there is ample evidence of the use of TMT for assessing processing speed, attention, and executive functioning (Reitan, 1992) as well as its use in detecting brain damage and predicting long-term outcomes following injury (Atchison et al., 2004; Himanen et al., 2009; Johnstone, Leach, Hickey, Frank, & Rupright, 1995; Lange, Iverson, Zakrzewski, Ethel-King, & Franzen, 2005; Periáñez et al., 2007), comparatively fewer studies have examined the ability of TMT-C to quantify the fundamental cognitive processes underlying performance in pediatric traumatic brain injury (TBI) populations. This is an issue, as children’s brains are not yet fully developed and therefore children may exhibit differential cognitive impairment following brain injury (Pennington, 1997). This may be particularly relevant regarding the Trails B subtest, which has been founds to be particularly reliant on the integrity of the cortical structure (Demakis, 2004; Pa et al., 2010; Sánchez-Cubillo et al., 2009; Stuss et al., 2001).

Studies have confirmed that performance on the TMT-C is impaired in children with acquired and neurodevelopmental disorders associated with cognitive deficits including learning disabilities, epilepsy, and TBI (Davids, Goldenberg, & Laufer, 1957; Mittelmeier, Rossi, & Berman, 1989; O’Leary, 1983; Reitan, 1971; Rourke & Finlayson, 1975; Sroufe et al., 2010). In addition, in pediatric TBI, the TMT-C has been found to differentiate severe injuries from mild and moderate injuries (Knights et al., 1991). A more recent study by Reitan and Wolfson (2004) compared Trails A and B performance among children with brain damage, children with learning disabilities, and controls and found that the brain-damaged sample took
significantly longer to complete both trails than either of the other groups and that Trails B classified the three groups across three levels of neuropsychological impairment. Studies examining variations of the TMT, such as the Comprehensive TMT (Reynolds, 2002) and the Children’s Color Trails Test (Llorente, Williams, Satz, & D’Elia, 2003), have also consistently documented universal impairment of performance on trails tests in brain-injured children (Allen, Haderlie, Kazakov, & Mayfield, 2009; Armstrong, Allen, Donohue, & Mayfield, 2008; Williams, Rickert, Hogan, & Zolten, 1995).

Although these studies confirm that trail tests can detect pediatric TBI, they provide little information on how separate cognitive mechanisms might differentially relate to TMT-C performance. Other studies examining adult populations generally agree that Trails A relies on processing speed, motor speed, visual scanning, and perceptual abilities, whereas Trails B additionally relies on working memory, inhibition, and other executive functions (Arbuthnott & Frank, 2000; Crowe, 1998; Langenecker, Zubiena, Young, Akil, & Nielson, 2007; Ríos, Periáñez, & Muñoz-Céspedes, 2004). A recent study by Sánchez-Cubillo and colleagues (2009) examined the construct validity of the TMT in a healthy senior sample and found that Trails A was primarily reliant on visuoperceptual abilities, whereas Trails B tapped into working memory and task-switching. No relation was found between motor speed and forward digit-span tasks and any of the trails scores. Though these results provide some guidelines for child studies, to date no study has examined the predictors of TMT-C performance in a pediatric TBI population even though these children are commonly administered some version of the TMT as part of the evaluation process. Such a study is warranted as brain damage is known to cause global and heterogeneous cognitive deficits in children as well as adults (Allen et al., 2010; Reitan & Wolfson, 1993) and the manner in which these deficits might influence performance on TMTs may differ given the neurodevelopmental differences between children and adults.

Several cognitive processes that are related to TMT and therefore likely related to TMT-C performance were examined in this study, including visuospatial processing speed, motor speed, attention, working memory, and cognitive inhibition. Based on the existing research, it was hypothesized that processing and motor speed would best predict performance on Trails A, whereas working memory and inhibition would predict performance on Trails B (Crowe, 1998; Sánchez-Cubillo et al., 2009).

Method

Participants

Participants included 61 children and adolescents between the ages of 9 and 14 years ($M = 11.7; SD = 1.8$) selected from a consecutive series of cases referred for neuropsychological evaluation at a pediatric specialty hospital following TBI. TBI was confirmed using appropriate laboratory, neuroimaging, and examinational findings. All participants had a primary diagnosis of TBI and no pre-injury neurological or neurodevelopmental disorders. Of the 61 participants, 36 (59.0%) were boys. The majority (86.9%) was right handed and all had sustained a closed head injury. Ethnicity was defined as 20 (32.8%) Caucasian, 8 (13.1%) African American, 8 (13.1%) Hispanic, and 25 (41.0%) did not report their ethnicity. Assessments were conducted an average of 10.9 months after time of injury ($SD = 9.7$; min = 3; max = 48; range = 45). Causes of TBI included motor vehicle accident (55.7%), being struck by a motor vehicle while on foot (21.3%), 4-wheeler accident (3.3%), bike accident (3.3%) skiing accident (9.8%), and other (6.6%). Glasgow Coma Scale (GCS) scores were available for 44 (72.1%) of the patients. The median GCS score (Teasdale & Jennett, 1974) was 7, and 25 (56.8%) of the sample sustained severe injuries, 15 (34.1%) sustained moderate injuries, and 2 (4.5%) sustained mild injuries. This study was completed in accordance with local institutional review board research standards.

Measures

TMT for older children. The TMT-C (Reitan & Wolfson, 1992) is a shortened version of the TMT, using 15 rather than the typical 25 target circles on each page. Similar to the adult version, the TMT-C is comprised of two individually administered parts (A and B). Part A requires participants to connect 15 circles containing incremental numbers in sequential order. Part B has 15 circles containing both numbers and letters and participants must alternate between numerical and alphabetical sequences, starting at 1 and connected to A, then connecting to 2, and so forth. This test was designed and normed for children between 9 and 14 years of age.

Wechsler Intelligence Scales. Participants completed the Wechsler Intelligence Scale for Children-Fourth Edition and the Digit Symbol—Coding and Symbol Search subtest scaled scores were selected and averaged to serve as a composite of processing speed (Allen et al., 2010; Donders and Janke, 2008).
Test of Memory and Learning. The Test of Memory and Learning (TOMAL; Reynolds & Bigler, 1994) is a memory battery designed for children, which assesses verbal and non-verbal long-term memory and learning as well as attention span. The Digits Forward (DF) and Letters Forward subtests were combined to assess forward attention span, and the Digits Backward (DB) and Letters Backward subtests were combined to assess working memory. Such a distinction was chosen because backward span tasks are generally thought to require a greater working memory load than forward span tasks (Reynolds, 1997).

Conners’ Continuous Performance Test-II. The Continuous Performance Test-II (CPT-II; Conners, 2000) is a measure of attention in which participants are prompted to press a button in the presence of target stimuli. Although primarily conceptualized as a measure of sustained attention, recent factor and validity studies have identified other latent subprocesses of attention, including focused and sustained attention, vigilance, and hyperactivity/impulsivity (Egeland & Kovalik-Gran, 2010a, 2010b). The current study included two composites derived from identified factors including Hyperactivity/Impulsivity, which is a measure of cognitive inhibition, and Sustained Attention.

Hyperactivity/Impulsivity was calculated from $t$-scores of CPT Commission Errors and Hit Reaction Time, which measure responses to distractors and average speed of correct responses, respectively. In order to match the direction of factors identified by Egeland and Kovalik-Gran (2010a), the Hit Reaction Time $t$-score was reversed before combining with the Commission $t$-score. Sustained Attention was calculated by averaging the Hit Reaction Time by Block Change and Standard Error by Block $t$-scores, which measure changes in reaction times and response consistency.

Grooved Pegboard Test

The Grooved Pegboard Test is a measure of motor speed and dexterity. Raw scores were time taken to place all the pegs in the board with the dominant and nondominant hands, which were converted to $t$-scores ($M = 50, SD = 10$) using available norms.

Data Analysis

Raw scores were standardized according to the manuals of their respective batteries and by norms offered by Spreen and Strauss (1998). Composite scores were created by summing and averaging scores that fit their theoretical domains. All predictors were examined via histogram plots to assess for normality within the distribution. Initial correlations and analyses of variance between TMT-C scores and relevant demographic variables were run to see whether gender, ethnicity, age, months since injury, or GCS scores significantly predicted trails performance, and if so, would serve as covariates in the regression analysis. Composites were next correlated with Trails A and B $t$-scores to examine significant relationships. As all composites represent constructs that have theoretical relevance with trails performance, Type I error was not controlled for. Rather, significant correlates with the TMT-C were indicators of possible predictors. All purported predictors were then entered into stepwise regression analyses with Trails A and B serving as predictors.

Results

Descriptive statistics for Trails A, Trails B, derived scores, and neuropsychological measures are displayed in Table 1. The Grooved Pegboard scores were skewed, and so a log transformation was performed to normalize the distribution. No significant

<table>
<thead>
<tr>
<th>Unit of measurement</th>
<th>$t$-score</th>
<th>Scaled score</th>
<th>log of $t$-score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TMT A</td>
<td>TMT B</td>
<td>CPTCom</td>
</tr>
<tr>
<td>Mean</td>
<td>38.9</td>
<td>45.8</td>
<td>48.9</td>
</tr>
<tr>
<td>SD</td>
<td>14.6</td>
<td>10.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Range</td>
<td>60.1</td>
<td>53.3</td>
<td>40.6</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.33</td>
<td>-0.71</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

Notes: TMT = Trail Making Test; CPT = Conners’ Continuous Performance Task; CPTCom = CPT Commission Errors; CPTHR = CPT Hit Reaction Time; CPTRTBC = CPT Reaction Time Block Change; CPTSEBC = Standard Error Block Change; DigCod = Wechsler Coding Subtest; DigSym = Wechsler Digit Symbol Search Subtest; DigFor = Test of Memory and Learning Digits Forward Subtest; LetFor = Test of Memory and Learning Letters Forward Subtest; DigBac = Test of Memory and Learning Digits Backward Subtest; LetBac = Test of Memory and Learning Letters Backward Subtest; GPB DOM = Grooved Pegboard Dominant Hand; GPD NDOM = Grooved Pegboard Nondominant Hand.
Differences or associations were found between trails scores and gender, ethnicity, age, months since injury, or GCS scores (p > .33 in all cases).

**Correlational Analysis**

Correlations between composites and TMT-C are presented in Table 2. Trails A had significant associations with the motor, processing speed, backwards span, and sustain components and Trails B had significant associations with processing speed, forward span, and backward span composites.

**Regression Analysis**

Multiple regression predictors for Trails A included the motor, processing speed, forward span, and sustain components and the overall model was significant (R² = .45, p < .02). Only processing speed had a significant unique contribution to predicting Trails A performance with higher scores associated with lower time needed to complete the test. Processing speed, forward span, and backward span composites were then entered as predictors of Trails B. The overall model was significant (R² = .33, p < .02) with higher backward span scores associated with faster Trails B completion time. See Table 3 for complete data.

**Discussion**

Results of this study provide insight into the neurocognitive constructs that mediate TMT-C performance in children with brain injury. As hypothesized, processing speed significantly predicted Trails A performance and working memory as measured by backward span tasks predicted Trails B performance, in concordance with TMT studies regarding other groups including clinical and normative samples (Crowe, 1998; Mahurin et al., 2006; Nelson, Yoash-Gantz, Pickett, & Campbell, 2009; Sánchez-Cubillo et al., 2009). Of interest, Sánchez-Cubillo and colleagues demonstrated similar findings in a sample of older healthy adults, but caution that such results may not be applicable to clinical populations. Our study indicates that at least for children with brain injury, these results do generalize. Correlational findings also indicate that motor speed,

---

### Table 2. Correlations of composite scores with TMT-C

<table>
<thead>
<tr>
<th></th>
<th>TMT-C A</th>
<th>TMT-C B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>.30*</td>
<td>.21</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>.41**</td>
<td>.25*</td>
</tr>
<tr>
<td>Forward Span</td>
<td>.14</td>
<td>.26*</td>
</tr>
<tr>
<td>Backward Span</td>
<td>.28*</td>
<td>.33*</td>
</tr>
<tr>
<td>Hyperactivity/Impulsivity</td>
<td>.02</td>
<td>.21</td>
</tr>
<tr>
<td>Sustained Attention</td>
<td>.27*</td>
<td>.01</td>
</tr>
</tbody>
</table>

*Note: All scores were transformed so that positive associations indicate better performance.*

*p < .05.

**p < .01.

### Table 3. Results from the regression analysis

<table>
<thead>
<tr>
<th></th>
<th>β-value</th>
<th>t-value</th>
<th>p-value</th>
<th>Partial</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMT-C A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing Speed</td>
<td>0.405</td>
<td>3.40</td>
<td>&lt;.01</td>
<td>0.405</td>
<td>1.00</td>
</tr>
<tr>
<td>Forward Span</td>
<td>-0.066</td>
<td>0.55</td>
<td>.55</td>
<td>-0.071</td>
<td>1.037</td>
</tr>
<tr>
<td>Motor</td>
<td>-0.093</td>
<td>0.63</td>
<td>.53</td>
<td>-0.082</td>
<td>1.538</td>
</tr>
<tr>
<td>Sustained Attention</td>
<td>-0.183</td>
<td>-1.51</td>
<td>.14</td>
<td>-0.194</td>
<td>1.059</td>
</tr>
<tr>
<td>TMT-C B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backward Span</td>
<td>0.326</td>
<td>2.65</td>
<td>.01</td>
<td>0.326</td>
<td>1.00</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>0.157</td>
<td>1.19</td>
<td>.24</td>
<td>0.155</td>
<td>1.146</td>
</tr>
<tr>
<td>Forward Span</td>
<td>0.126</td>
<td>0.89</td>
<td>.38</td>
<td>0.116</td>
<td>1.318</td>
</tr>
</tbody>
</table>

*Note. TMT-C = Trail Making Test for Children; VIF = Variance Inflation Factor.*
forward span tasks, and sustained attention to correlate with TMT-C scores but much of this variance can be better accounted for by processing speed for Trails A and backward tasks for Trails B.

Slowed processing speed is a common deficit following pediatric TBI and has a dose–response relationship with severity over recovery periods (Catroppa & Anderson, 2003). In addition, processing speed predicts cognitive functioning in children with TBI (Donders & Minnema, 2004). As results from this study firmly establish that Trails A performance is mediated primarily by processing speed, this subtest is likely useful for estimating overall severity and cognitive functioning immediately post-injury as well as during recovery.

Of some surprise, motor speed as measured by the Grooved Pegboard Test did not predict Trails A performance. Given the speed component of both tasks, it might be expected that there would be some association between tests. However, one study by Kennedy and colleagues (2003) examined predictors of processing speed in adults who sustained TBI and found that motor speed made only a minute contribution to PSI scores, suggesting that the two are mediated by separate processes. Specifically, Trails A requires visual discrimination and scanning (Sánchez-Cubillo et al., 2009) as well as mental speed, while the Grooved Pegboard Test is primarily a measure of psychomotor speed. Psychomotor speed may be more impaired in individuals whose sustain brain injury directly related to associated motor regions or those with neurological disorders specifically linked to motor impairment, such as Parkinson’s disorder or multiple sclerosis (Kennedy, Clement, & Curtiss, 2003). In any case, it appears that in a heterogeneous sample of children with TBI, processing speed is the primary predictor of Trails A performance.

Backward span tasks are thought to place greater demands on working memory than forward span tasks (Brandling et al., 2003; Owen, Lee, & Williams, 2000; Ramsay & Reynolds, 1995) and so DF and DB were separately assessed in this study. As hypothesized, the backward span task composite significantly predicted Trails B performance. Poorer performance on Trails B has in turn been linked to impairment in working memory and executive functions in adult clinical populations (Demery, Larson, Dixit, Bauer, & Perlstein, 2010; Sánchez-Cubillo et al., 2009). Notably, the forward span tasks did not predict performance on the TMT-C, providing support that backward span tasks are unique in providing relevant clinical information in TBI populations (Demery et al., 2010). From a clinical perspective, it might be worthwhile then to separately examine forward and backward span tasks as measuring different aspects of phonological memory in pediatric TBI, with backward tasks tapping into working memory which in turn mediates performance on Trails B.

Cognitive inhibition has been reported to predict Trails B performance in adults (Arbuthnott & Frank, 2000) but this was not found in our sample as measured by the CPT-II Hyperactivity/Impulsivity factor. This may be related to differences in the cognitive processes mediating executive control in children due to frontal lobe immaturity (Jacobs, Harvey, & Anderson, 2011). For example, Bello and colleagues (2008) examined the Children’s Category Test, another purported measure of executive control, in a pediatric TBI sample and found it to lack sensitivity to brain dysfunction. It may be that cognitive inhibition is responsible for mediating Trails B performance in adults but not for children. Further studies should specifically evaluate the role of cognitive inhibition in task performance across the developmental lifespan.

These results support the hypothesis that mechanisms of working memory predict TMT-C Trails B scores, whereas processing speed is a primary influence of Trails A scores in children with brain damage. Other demographic and clinical variables that have been previously linked to TMT performance, including age, months since injury, and severity of injury (Lange et al., 2005), were not found to influence performance in this sample. This suggests that the observed relationships between working memory and processing speed and TMT-C performance are consistently present in children who have sustained TBI. Slowed performance of Trails A and B can likely be partially attributed to impairment in the constructs that mediate their completion times and assist clinicians in predicting outcome and treating planning.

Limitations should be addressed. The current study relied on retrospective data with no available corroborating neuroimaging data. As Trails B performance is affected by lesions throughout the brain (Demakis, 2004), it is uncertain if any specific cortical regions underlie the relationship between backward span tasks and Trails B scores. However, evidence suggests that the “switching” nature of Trails B is specifically mediated by the dorsolateral and medial prefrontal cortex in adults (Moll, de Oliveira-Souza, Moll, Bramati, & Andreiuolo, 2002). It may be worthwhile to establish to degree to which these prefrontal regions might predict Trails B performance in children. There are other cognitive components that may predict TMT-C scores including shifting attention and visual scanning that were not accounted for in this study. Further studies should focus these additional factors that might predict the performance as well as provide the neuroimaging data that could provide the sources of cognitive impairment that in turn relates to the TMT-C.

Funding

None.
Conflict of Interest

None declared.

References


