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RESEARCH ARTICLE

# Measuring Executive Function Using Eye Movements on a Computerized Trail Making Test: A Pilot Study

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## Abstract

**Objective**: The current study investigated the validity of a novel computerized version of the Trail Making Test, and tested whether the integration of eye-tracking increased specificity and predictive power with other tests of executive function. We were specifically interested in whether eye movements, recorded during the completion of a computerized version of the Trail Making Test, served as a predictor of executive function as measured by the computerized Wisconsin Card Sorting Test.

**Methods**: Forty participants completed the pencil-and-paper Trail Making Test, the computerized Wisconsin Card Sorting Test and the computerized Trail Making Test. Eye movements were recorded during the completion of the computerized Trail Making Test.

**Results**: Eye-tracking measures for part B of the computerized Trail Making Test were correlated with T-scores for perseverative and non-perseverative responses/errors on the computerized Wisconsin Card Sorting Test. Hierarchical linear regression revealed that eye-tracking measures predicted variance for perseverative and non-perseverative errors/responses on the computerized Wisconsin Card Sorting Test, above and beyond Trail Making Test completion time.

**Conclusions**: The current pilot study supported the use of computerized versions of the Trail Making Test and provided preliminary evidence that eye movements may significantly add to the specificity in assessing executive function using the Trail Making Test.

**Keywords:** Trail Making Test, Executive Function, Eye Tracking, Wisconsin Card Sorting Test, Computerized Test Administration

## Introduction

Neuropsychological assessment is the performance-based evaluation of cognitive function that targets primary areas including attention, memory, processing speed, memory, language, and executive function. Neuropsychological tests are typically administered in verbal/written format and occasionally via computers[1]. Benefits of computerized tasks include the standardization of test administration, increased precision, cost-effective administration and automated data export/analysis[2].

Several neuropsychological assessments have been successfully converted to computerized formats. For example, the Trail Making Test (TMT) measures executive function, task switching, visual attention and psychomotor processing speed[3]. The traditional pencil-and-paper task requires participants to connect a series of 25 encircled numbers in ascending order (Part A; TMT-A) followed by a series of alternating numbers and letters (Part B; TMT-B)[4]. The primary outcome measure involves completion time for each part. Recently developed computerized versions of the TMT have been found to have higher test-retest reliability and specificity[5,6,7] and the opportunity for repeated test administration without discernable practice effects[8].

Another benefit of computerized neuropsychological assessments is facilitated integration with other technologies such as eye-tracking. Eye-tracking provides a precise method of measuring the online demands involved in cognitive processing in real time. Processing demands are reflected by several aspects of eye movement behavior, including fixations (maintained foveal position during information acquisition) and saccades (foveal movement from one point to another)[9]. As they pertain to visual search tasks, a large body of evidence has found that increased visual search complexity (associated with increased executive demands) is related to decreased saccade length and increases in saccade latencies (i.e., the delay prior to initiating a saccadic eye-movement), fixation durations, and fixation count[9]. Hicks and colleagues[10] integrated eye-tracking with a computerized version of the TMT. Their goal was to create an oculomotor-controlled paradigm that could be administered to individuals with language/motor impairments. The authors found correspondence between Part B of the oculomotor task and the standard written version of the TMT-B. Because the goal of Hicks et al.'s study was paradigm validation, the authors did not analyze eye-tracking data beyond the correspondence between the two TMT tasks. In addition to the administration advantages highlighted by Hicks et al., the availability of eye-movement data for visually-based neuropsychological tests, such as the TMT, provides a rich source of information elucidating the online components of cognitive processing.

The current study aimed to assess the utility of eye movement data to evaluate executive function in a computerized version of the TMT. A common criticism of the TMT is the lack of specificity associated with the single measure of completion time[8]. Eye movements can provide more detailed insights into online executive planning, cognitive flexibility, distraction and perseveration during TMT completion. Furthermore, the precision afforded by eye movements allows for increased differentiation between the mechanisms associated with the TMT-A vs. the TMT-B. Specifically, the TMT-A is primarily predicted by visual search and processing speed[11,12], while the TMT-B is associated with higher-level executive functions such as mental flexibility, working memory and inhibition control[13,14]. Performance on the TMT-B, in particular, has been found to correspond with other measures of executive function such as the Wisconsin Card Sorting Test (WCST)[14,15,16], which contains specific measures reflecting perseveration/cognitive flexibility (i.e. perseverative errors), distractibility/inhibition (non-perseverative errors) and failure to maintain set.

The goals of the current study were to 1) investigate whether a novel computerized version of the TMT (c-TMT) is comparable to the original paper and pencil version 2) investigate whether a difference exists in the relationship between the c-TMT-B and the TMT-B with performance on a computerized version of the WCST (c-WCST[17,18]) 3) investigate whether eye-tracking can predict performance on the c-WCST above and beyond standard TMT-B completion times. Preliminary evidence supporting a relationship between measures on the c-WCST and eye movements during c-TMT completion would add to the specificity of the TMT and allow for a higher degree of comparison between two of the most frequently used measures of executive function.

## Method

### *Participants*

Forty-six undergraduate participants were recruited for the current study (33 female). All data included in this manuscript was obtained in compliance with regulations of the University of British Columbia Okanagan Research and Ethics Board. Exclusion criteria involved having previously received a neuropsychological evaluation for any reason, having a history of brain injury, neurodegenerative disease, mental illness, or having uncorrected visual impairment. 4 participants were removed from analysis due to tracking loss during eye-movement recording (i.e., >20% of eye movement data missing). 2 were removed due invalid profiles on the c-WCST (i.e., random response patterns with no categories completed). Thus, results below are based on 40 participants (27 female) between the ages of 18 and 44 years ($M$ = 20.33, $SD$ = 4.35) with an average education of 13.3 years ($SD$=0.99). Each participant completed the c-WCST, the c-TMT, and the pencil-and-paper version of the TMT.

### *Measures*

*Computerized WCST*. The c-WCST[18] is a computerized version of the WCST. Participants are instructed to choose one of four target cards that matched a test card in shape, color, or number of stimuli. Computer feedback indicates whether the response is correct. The sorting criteria change after 10 consecutive correct responses and subjects are required to use a different sorting strategy.

*Pencil-and-Paper TMT*. The TMT was administered in accordance with Reitan[4] and using normative data from Tombaugh[19].

*Computerized TMT.* A computerized version of the TMT was developed based on the pencil-and-paper version. Unlike previous computerized adaptations of the TMT, the current version used a stylus and trackpad to complete the task. Specifically, the TMT testing pages were presented on the computer screen and participants sequentially connected the target circles using the stylus on a trackpad, which was placed adjacent to the computer (as opposed to a mouse; e.g., Woods et al.[6]; Zeng et al.[8]). Participants visually attended to the screen while tracing the stylus over the trackpad and eye movements were recorded. The logic for the paradigm was designed using JAVA script and the user interface was developed using JAVA FX8. We integrated an INTUOS ART trackpad and stylus, (Wacom Technology Corporation). The overall tablet size was 10.8" x 8.5" and the active area, in the center of the tablet, was 8.5" x 5.3".

A tracer line displayed the onscreen path of the stylus over the trackpad. If a participant breached the perimeter of a circle, the color of the circle's perimeter changed from black to green. If the participant's line entered an incorrect circle, the line between the most recent correct circle and the newly entered incorrect circle turned to red. A message then flashed repeatedly on the screen reading: "PLEASE, GO BACK TO THE LAST CORRECT CIRCLE". If a participant had not entered a new correct circle in the proper sequence for 10 seconds, then the next appropriate circle in the sequence would flash repeatedly until it was entered.

We implemented portrait orientations to the paradigm that were identical to those employed in the manual test. The testing pages were slightly smaller than the original version to accommodate the Dell Precision M4800 laptop screen size (15.6" screen; resolution of 1366 x 768). The tasks were completed in the same order as the manual version of the TMT.

### *Procedure*

Each participant completed the TMT and c-TMT, counterbalanced for order. The c-WCST was administered between the TMT and c-TMT to minimize practice effects. Eye movements were tracked using an SMI RED-m remote system sampling at 120 Hz and SMI Experiment Suite™ 360° software. Screen resolution was set at 1920x1080 pixels with a refresh rate of 60 Hz. The screen was centered on the mid-sagittal plane of the subject's head and was viewed binocularly from a distance of 60cm. Head position was maintained with the use of a chinrest. We employed a 5-point calibration and 4-point validation routine for each participant. Fixations within 0.4 degrees on both the x- and y-axes were deemed acceptable. We used software specific to the SMI system (BeGaze™) to identify eye-movement variables and remove blink data.

Fixations were defined with a maximum dispersion of 2° of visual angle and a minimum duration of 80 msec (native SMI settings).

A brief maze task was administered prior to the administration of the c-TMT to condition participants to use the trackpad.

## Results

Completion times for the TMT (A & B) and the c-TMT (A & B) did not vary according to administration order (TMT-A: *F*(1,39)=0.15, *p*=0.70; TMT-B: *F*(1,39)=0.72, *p*=0.40; c-TMT-A: *F*(1,39=0.88, *p*=0.36; c-TMT-B: *F*(1,39)=0.02, *p*=0.88). Findings indicated a moderate correlation between completion time on the computerized and written versions of TMT-A ($r = .46$, $p = .002$) and a strong correlation for TMT-B ($r = .57$, $p < .001$). Completion times for c-TMT-A (*M* = 35.05s, *SD* = 6.47s) were significantly longer than for TMT-A (*M* = 21.50s, *SD* = 5.59s; *t*(39) = 7.35, $p < .001$). Similarly, completions times for c-TMT-B (*M* = 57.8s, *SD* = 15.84s) were longer than for TMT-B (*M* = 48.18s, *SD* = 14.34s; *t*(39) = 3.90, $p < .001$). Mean outcome scores for measures on the TMT and the c-WCST were within normal limits according to published norms.

Consistent with previous investigations, there was an overall lack of a correlational relationship between completion time for TMT-A and measures on the c-WCST. Similarly, eye-tracking measures on c-TMT-A were not related to c-WCST performance (Table 1).

Table 1: *Correlations coefficients (r) between performances on the computerized Wisconsin Card Sorting Test, completion times for parts A and B of the paper and pencil and computerized Trail Making Tests, and eye-tracking measures for parts A and B of the computerized Trail Making Test.*

| | | Computerized Wisconsin Card Sorting Test | | | | | |
|---|---|---|---|---|---|---|---|
| | | Total Errors (T-score) | Perseverative Responses (T-score) | Perseverative Errors (T-score) | Non-Perseverative Errors (T-score) | Conceptual Level Responses (T-score) | Total Categories Completed |
| Pencil-Paper TMT | TMT-A Completion Time (sec) | -0.13 | -0.10 | -0.09 | -0.07 | -0.03 | -0.16 |
| | TMT-B Completion Time (sec) | -0.10 | -0.32* | -0.31 | -0.07 | -0.13 | -.363* |
| Computerized TMT-A | Completion Time (sec) | 0.00 | 0.01 | 0.04 | 0.07 | -0.21 | -0.01 |
| | Fixation Count | -0.16 | -0.09 | -0.06 | -0.10 | -0.20 | -0.09 |
| | Dwell Time (ms) | -0.17 | -0.11 | -0.08 | -0.14 | -0.17 | -0.10 |
| | Fixation Dispersion (px) | -0.16 | -0.10 | -0.07 | -0.11 | -0.18 | -0.08 |
| | Saccade Count | -0.16 | -0.09 | -0.06 | -0.10 | -0.19 | -0.09 |
| | Saccade Distance (°) | -0.16 | -0.09 | -0.06 | -0.11 | -0.17 | -0.08 |
| | Saccade Velocity (°/s) | -0.16 | -0.09 | -0.05 | -0.10 | -0.17 | -0.10 |
| | Saccade Latency (ms) | 0.13 | -0.03 | -0.07 | -0.08 | 0.12 | 0.14 |
| Computerized TMT-B | Completion Time (sec) | -0.08 | -0.32* | -0.29 | -0.02 | -0.21 | -0.27 |
| | Fixation Count | -0.34* | -0.40* | -0.40* | -0.46** | 0.06 | -0.26 |
| | Dwell Time (ms] | -0.28 | -0.38* | -0.40* | -0.45** | 0.07 | -0.21 |
| | Fixation Dispersion [px) | -0.31 | -0.38* | -0.38* | -0.45** | 0.07 | -0.23 |
| | Saccade Count | -0.34* | -0.40* | -0.40* | -0.46** | 0.07 | -0.25 |
| | Saccade Distance (°) | -0.31 | -0.39* | -0.38* | -0.44** | 0.06 | -0.23 |
| | Saccade Velocity (°/s) | -0.32* | -0.39* | -0.38* | -0.45** | 0.06 | -0.24 |
| | Saccade Latency (ms) | -0.30 | -0.52** | -0.50** | -0.20 | -0.15 | -0.24 |

*$p \leq .05$

**$p \leq .01$

As presented in Table 1, TMT-B completion times correlated negatively with c-WCST Perseverative Response T-scores and Total Categories completed. Completion times for the c-TMT-B task demonstrated a similar relationship with Perseverative Responses but did not reach significance for Categories completed. Eye-tracking measures for the c-TMT-B were significantly correlated with scores on the c-WCST. Fixation count, dispersion and total dwell time were negatively correlated with T-scores for both perseverative and non-perseverative responses and errors. Saccade count, distance and velocity were also negatively correlated with T-scores for both perseverative and non-perseverative responses and errors. Saccade latency was related only to perseverative responses/errors.

Hierarchical multiple linear regression analysis was conducted to investigate whether eye-tracking measures could account for variance in c-WCST performance, above and beyond standard TMT-B completion time (Table 2). Three models were contrasted in their ability to predict T-scores for perseverative responses, perseverative errors and non-perseverative errors on the c-WCST. Model 1 consisted solely of demographic variables, Model 2 included TMT-B completion time and Model 3 included eye-tracking measures from the c-TMT (see Table 2 for individual variables). For perseverative responses, inclusion of TMT-B completion time accounted for 22% of the variance (Adj. $R^2$=0.14; $F(4,36)$=2.52, $p$=.06) and represented a significant change from demographic variables alone ($\Delta R^2$=0.15; $F(1,39)$=6.63, $p$=0.01). The inclusion of eye-tracking measures led to a significant increase in $R^2$ by 39% ($F(7,33)$=4.07, $p$=.003), thus accounting for 61.5% (Adj. $R^2$=0.47) of the total variance in perseverative response T-scores. Average saccade latency was the only significant contributor to Model 3 ($\beta$= -0.62, $p$<.001). For perseverative errors, inclusion of TMT-B completion time accounted for 24% of the variance (Adj. $R^2$=0.16; $F(4,36)$=2.79, $p$=.04) and represented a significant change from demographic variables alone ($\Delta R^2$=0.15; $F(1,39)$=6.93, $p$=0.01). Inclusion of eye-tracking measures led to a significant increase in $R^2$ ($F(7,33)$=3.99, $p$=.004), accounting for 62% (Adj. $R^2$=0.47) of the total variance in perseverative error T-scores. Years of education and average saccade latency were both significant contributors to Model 3 ($\beta$ = -.34, $p$=.03 and $\beta$= -0.58, $p$<.001 respectively). For non-perseverative errors, inclusion of TMT-B completion time accounted for 18% of the variance (Adj. $R^2$=0.09; $F(4,36)$=1.93, $p$=.12) and did not represent a significant change from demographic variables alone ($\Delta R^2$=0.02; $F(1,39)$=1.04, $p$=0.32). Inclusion of eye-tracking measures led to a significant increase in $R^2$ by 29% ($F(7,33)$=2.22, $p$=.05), thus accounting for 47% (Adj. $R^2$=0.27) of the total variance in non-perseverative error T-scores. There were no individual significant contributors to Model 3.

*Table 2: Hierarchical linear regression co-efficients for three models predicting perseverative responses, perseverative errors and non-perseverative errors on the computerized Wisconsin Card Sorting Task. Independent variables included demographics (Model 1), completion time for the pencil-and-paper TMT-B task (Model 2), and eye tracking measures from the c-TMT-B task (Model 3).*

| | | Model 1 | | | Model 2 | | | Model 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | c-WCST Pers. Resp. | c-WCST Pers. Errors | c-WCST Non-Pers. Errors | c-WCST Pers. Resp. | c-WCST Pers. Errors | c-WCST Non-Pers. Errors | c-WCST Pers. Resp. | c-WCST Pers. Errors | c-WCST Non-Pers. Errors |
| Age | B | 0.15 | 0.15 | -0.21 | 0.14 | 0.14 | -0.22 | 0.09 | 0.08 | -0.22 |
| | β | 0.06 | 0.06 | -0.12 | 0.05 | 0.05 | -0.12 | 0.04 | 0.03 | -0.12 |
| Education | B | -1.74 | -2.72 | -1.54 | -2.55 | -3.56 | -1.78 | -3.07 | -3.91* | -2.00 |
| | β | -0.15 | -0.24 | -0.19 | -0.23 | -0.31 | -0.22 | -0.27 | -0.34* | -0.25 |
| Gender | B | -4.95 | -4.00 | -4.24 | -5.88 | -4.95 | -4.50 | -2.00 | -1.41 | -3.11 |
| | β | -0.21 | -0.17 | -0.25 | -0.25 | -0.21 | -0.27 | -0.08 | -0.06 | -0.19 |
| TMT-B Completion Time (sec) | B | - | - | - | -0.31** | -0.32** | -0.09 | -0.02 | -0.05 | 0.02 |
| | β | - | - | - | -0.39** | -0.40** | -0.16 | -0.03 | -0.06 | 0.04 |
| c-TMT-B Fixation Count | B | - | - | - | - | - | - | -0.01 | 0.01 | 0.04 |
| | β | - | - | - | - | - | - | -0.73 | 1.12 | 4.63 |
| c-TMT-B Dwell Time (ms) | B | - | - | - | - | - | - | 0.00 | 0.00 | 0.00 |
| | β | - | - | - | - | - | - | 0.24 | -0.21 | 0.18 |
| c-TMT-B Fixation Dispersion (px) | B | - | - | - | - | - | - | 0.00 | 0.00 | 0.00 |
| | β | - | - | - | - | - | - | 4.47 | 4.48 | 0.24 |
| c-TMT-B Saccade Count | B | - | - | - | - | - | - | -0.07 | -0.10 | -0.09 |
| | β | - | - | - | - | - | - | -5.37 | -7.54 | -10.08 |
| c-TMT-B Saccade Distance (°) | B | - | - | - | - | - | - | 0.00 | 0.00 | 0.01 |
| | β | - | - | - | - | - | - | -0.20 | 1.61 | 5.96 |
| c-TMT-B Saccade Velocity (°/s) | B | - | - | - | - | - | - | 0.00 | 0.00 | 0.00 |
| | β | - | - | - | - | - | - | 1.29 | 0.25 | -1.35 |
| c-TMT-B Saccade Latency (ms) | B | - | - | - | - | - | - | -0.13** | -0.12** | -0.03 |
| | β | - | - | - | - | - | - | -0.62** | -0.58** | -0.21 |
| $R^2$ | | 0.76 | 0.92 | 0.16 | 0.22 | 0.24 | 0.18 | 0.62 | 0.62 | 0.47 |
| F | | 0.99 | 1.21 | 2.23 | 2.52 | 2.79* | 1.93 | 4.07** | 4.17** | 2.29* |
| $\Delta R^2$ | | - | - | - | 0.15 | 0.15 | 0.02 | 0.39 | 0.38 | 0.29 |
| Δ F | | - | - | - | 6.63** | 6.93** | 1.04 | 4.07** | 3.99** | 2.22* |

*$p \leq .05$

**$p \leq .01$

## Discussion

The current pilot study represents a preliminary investigation into the relationship between eye movements on a computerized version of the Trail Making Test (c-TMT) and performance on the Wisconsin Card Sorting

Test (computerized version; c-WCST). We were interested in whether c-TMT-B eye movements served as a better predictor of c-WCST performance compared to the standard measure of TMT-B completion time. Characteristics associated with eye fixations and saccadic eye movements, during the completion of the c-TMT-B, were negatively correlated with perseverative and non-perseverative error T-scores. Interestingly, saccade latency was related only to perseverative error/response rates. Hierarchical regression analysis revealed that eye-tracking measures predicted perseverative errors and responses and non-perseverative errors above and beyond standard TMT-B completion times. Among the eye-tracking measures, saccade latency was identified as a significant contributor to models predicting perseverative errors and responses.

A perseverative error occurs when an individual persists in responding to a stimulus characteristic that is incorrect[20]. Results from the current study are consistent with previous findings[14] demonstrating that TMT-B (but not TMT-A) completion times are related to perseverative error rates on the WCST. The increased task demands of c-TMT-B, and different sequence patterns required for completion, are conceptually similar to set-shifting in the WCST. Therefore, it is unsurprising that participants who struggled to switch sets in the c-WCST take longer to complete TMT-B. Our finding that saccade latency, during c-TMT-B completion, accounts for more variance in perseverative error and response scores suggests that the relationship between longer test completion and perseverative errors may stem specifically from delays in encoding the visual target and initiating the appropriate eye saccade.

Unlike perseverative errors, WCST non-perseverative errors result from a failure to maintain stimulus attention while inhibiting interference from co-existing stimuli[20]. Here we found that standard TMT-B completion times did not significantly predict non-perseverative error scores. The inclusion of our eye-tracking variables, during the completion of c-TMT-B, resulted in significant improvement in the model. Eye-tracking investigations of visual search tasks indicate that eye movements and fixations are specifically related to search task complexity[21]. Therefore, we can speculate that individuals who have difficulty inhibiting co-existing stimuli on the WCST experience similar difficulties with distraction on TMT-B. Among neurologically healthy adults, such distractions may not affect overall completion time on a speeded visual search task but are detectable using more specific psychophysiological measures such as eye-tracking.

With respect to limitations, it should be noted that while our c-TMT completion times correlated with the standard pencil-and-paper task, the relationship was not as strong as those reported in previous computerized TMT developments[5,6,8]. Furthermore, completion times for both c-TMT-A and B were significantly longer than their pencil-and-paper counterparts. This may have resulted from difficulty using the stylus in the current task and may have influenced eye-movement measures. It is recommended that follow-up studies investigate the relationship between TMT eye movements and WCST performance using other established c-TMT tests to investigate the consistency of the current findings and expand upon the current pilot analysis.

## Conclusion

The current pilot study provides preliminary evidence that eye movement measures may significantly add to the specificity in assessing executive function using the TMT. Congruence between eye movements, during the completion of c-TMT-B, and performance on the c-WCST suggests that eye-tracking measures offer insights into executive function process demands that may not be captured by standard TMT completion time. Furthermore, our results are consistent with previous studies that highlight the benefits of adapting traditional neuropsychological tests for use with computerized platforms. Overall, eye tracking has shown considerable potential to improve our understanding of cognition, and cognitive deficits, in real time. Future research is warranted to investigate the application of eye-tracking methods within neuropsychological practice.

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## Compliance with Ethical Standards

### Conflict of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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No funding was received for conducting this study.

### Research Involving Human Participants

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the Research Ethics Board at the University of British Columbia Okanagan.

### Informed Consent

Informed consent was obtained from all individual participants included in the study.

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