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Digital Trail Making Test Performance in Individuals With Homonymous Hemianopia: The Effects of Visual Field Defect Location and Test Item Location on Task Performance

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Abstract

The Trail Making Test (TMT) is a widely-used assessment tool in neuropsychological research and clinical practice. Despite the widespread use of the Trail Making Test (TMT), little is known about how individuals with homonymous hemianopia (HH) perform on the test. This study examines the TMT performance of individuals with HH in comparison to individuals with acquired brain injury without visual defects (ABI w/o VFD) and neurologically healthy controls (HC). The study also examined whether the location of test items in the intact or blind hemifield had an impact on the TMT performance of individuals with HH. Results indicated that the HC group exhibited superior overall TMT performance compared to the other groups, as evidenced by their significantly shorter completion times on the TMT. No other significant differences in overall TMT performance between subjects with HH and subjects with ABI without visual field defects were found. Contrary to expectations, the location of test items in the blind or intact hemifield did not appear to have a significant effect on the TMT performance of individuals with HH. Additionally, the study found no significant difference in the ability of individuals with ABI w/o VFD to detect test items located in the blind hemifield of individuals with HH, indicating that the presence or absence of visual field defects did not significantly affect TMT performance in this sample.

Keywords; Trail Making Test, homonymous hemianopia, visual field defects, acquired brain injury

Trail Making Test Performance in People with Homonymous Hemianopia

Homonymous hemianopia (sometimes referred to as homonymous hemianopsia, HH) is a visual field defect involving a total loss of vision in either the two right or left halves of the visual fields for both eyes (Goodwin, 2014; Woldberg & Kapoor, 2022). Importantly, these visual defects cannot be explained by an injury to the eye itself, but they rather result from insults to the cerebral part of the visual system (de Haan et al., 2015; Pail et al., 2017; Perez & Chokron, 2014). HH is thus not characterized by impaired eye function nor blindness, but by a loss of visual information processing in the brain. To be more precise, this type of visual field loss is indicative of lesions involving the visual pathways distal to the optic chiasm (Pail et al., 2017). Neuroimaging has shown that lesions usually occur in the occipital- or parietal regions contralateral to the side of the visual field defect (Perez & Chokron, 2014).

HH can be caused by a variety of disorders affecting the brain including inflammation, tumors, traumatic head injuries, and cerebrovascular conditions (Perez & Chokron, 2014; Zhang et al., 2006a; Zihl et al., 2021). It has been estimated that stroke is the most frequent etiology and accounts for up to 70% of HHs (Goodwin, 2014; Zhang et al., 2006b;). Consecutively, up to 30% of stroke patients are experiencing HH (Pambakian, 2004) and in 8-10% of these individuals HH is permanent (Goodwin, 2014; Zhang et al., 2006). Other research has demonstrated that spontaneous recovery and improvement occur in at least 50% of people diagnosed with HH (Giorgi et al., 2009). The exact prevalence rate of HH within the general population is unknown. However, Gilhotra and colleagues (2002) identified homonymous visual field defects in 0.8% of participants in a defined older population (n = 3654, aged ≥49). According to Goodwin (2014), with the aging of the general population, it is expected that the prevalence of strokes and resultant HH is going to increase further.

Persistent visual field defects can predispose individuals with HH to debilitating con-

sequences (de Haan et al., 2015; Goodwin, 2014; Mannan et al., 2010; Perez & Chokron, 2014). More specifically, individuals suffering from HH exhibit locomotion disabilities, particularly outdoors (Giorgi, 2009; Goodwin, 2014; Perez & Chokron, 2014). These difficulties may manifest by bumping into objects or pedestrians and the inability to detect hazards in their blind hemifield (Perez & Chokron, 2014). Moreover, people with HH may face difficulties with navigating, cycling, driving a car, or reading (Keller & Lefin-Rank 2010; Nelles et al., 2010). In addition to these well-known difficulties, de Haan and colleagues (2015) reported that a high proportion of individuals with HH experiences problems with perception of depth, light sensitivity, and color vision. Unfortunately, the difficulties mentioned previously further decrease the individual's independence, limit employment opportunities, and increase the risk of mood disorders and physical injuries (e.g. by falling) (Goodwin, 2014; Perez & Chokron, 2014).

As described above, the homonymous visual field defects constitute a persistent burden to the affected individuals, but previous work has mainly investigated the motor and language effects of stroke (Frolov et al., 2017). However, some studies utilizing eye tracking and infrared recording techniques have yielded some important findings about visual disturbances associated with HH. Zihl and colleagues (2021) found that individuals with HH do not only experience impaired visual processing due to the restricted visual field, but they also exhibited disorganized scanning eye movements during a compensatory eye movement training. More precisely, these individuals adopt highly time-consuming, unsystematic, and irregular visual search strategies (Hazelton et al., 2020; Sahraie et al., 2016; Zihl et al., 2021). Furthermore, Zihl (1995) observed that people with HH display oculomotor behavior defined by inaccurate and irregular saccades directed towards the affected side of the visual field. In a recent systematic review, Elfeky and colleagues (2021) reported that individuals with HH tend to spend

more time gazing towards their blind hemifield to bring more of the visual scene into the intact hemifield. The visual scanning in the blind hemifield is characterized by a high number of refixations and repetitions of scan paths (Elfeky et al., 2021; Ishiai et al., 1987; Sahraie et al., 2016). It is important to note that individuals with HH exhibit these patterns of disorganized scanning to a lesser degree in the intact hemifields as well(Sahraie et al., 2016; Zihl, 1995).

These abnormal patterns of eye movements have been reported in 60% of individuals suffering from HH and some have referred to this subgroup as "pathological hemianopics" (Sahraie et al., 2016; Zihl, 1995). The scanning behavior of the remaining 40% of people with HH has been reported to be comparable to that of neurologically healthy individuals (Sahraie et al., 2016; Zihl, 1995). Further research has added that people with HH exhibit head scans towards the affected hemifield which tend to be of a small magnitude (Bowers et al., 2014; Lévy-Bencheton et al., 2016). The small magnitude of these head scans can result in impaired exploration and might contribute to difficulties of detecting stimuli located in the blind hemifield (Bowers et al., 2014; Goodwin, 2014; Pail et al., 2017).

As mentioned above, research examining the visual disturbances of HH is sparse, and there are also only a few authors that have addressed the performance of individuals with HH on certain neuropsychological tests relying on visual-spatial orientation (Tant, 2002). Tant and colleagues (2002) are among the few authors that have addressed this topic, with a study linking driving performance of individuals with HH to visuospatial test performance. Despite this, in-depth knowledge about the performance of individuals with HH on neuropsychological tests relying on visuospatial components is limited and normative data is missing. As a consequence, practitioners assessing the level of cognitive functioning of individuals with HH cannot relate the individuals' neuropsychological performance to their corresponding comparison group. Without this knowledge, it may be difficult to make an objective clinical judg-

ment about the level of cognitive functioning of individuals with HH. This might not only lead to misdiagnosing and the development of insufficient treatment plans but also potentially limits our understanding of the impact of HH on daily functioning. One neuropsychological test lacking normative data for people with HH is the well-known Trail Making Test.

The Trail Making Test (TMT) is among the most common and popular assessment techniques used in neuropsychological research as well as clinical practice worldwide (Kopp et al., 2015). This is due to the fact that the TMT is easily administrable and has proven to be a sensitive tool for detecting brain dysfunction (Salthouse & Fristoe, 1995). More precisely, poor performance on the TMT has been associated with different types of neurological and psychiatric disorders, in particular with frontal lobe lesions (Kopp et al., 2015). As a consequence, the TMT is now a standard diagnostic instrument in clinical settings.

Traditionally, the TMT is a paper and pencil test consisting of two parts (part A and part B). On TMT-A the subject is required to connect 25 numbered circles, which are randomly distributed, in ascending order (1-2-3) (Bowie & Harvey, 2006). On TMT-B the subject must alternate between numbers and letters (1-A-2-B-3-C). Usually, the TMT performance is indexed by the total time to completion with lower scores indicating better performance. In recent years, digital versions of the TMT (dTMT) have been introduced, which closely resemble the original version. The dTMT is designed to not only measure test performance more accurately than the traditional paper and pencil version but also to provide additional information (Dahmen et al., 2017). For instance, a touchscreen is used to report detailed timing information, pauses, and pencil lifts (Dahmen et al., 2017; Salthouse & Fristoe, 1995). In general, TMT scores highly correlate with dTMT scores, indicating that both measures capture the same aspects (Dahmen et al., 2017).

Although there is little consensus in the literature on which exact abilities are captured by the TMT (Kopp et al., 2015, Sanchez-Cubillo et al., 2009), various authors have suggested that TMT-A provides a baseline measure of psychomotor speed, working memory, general intelligence, visual attention, visuospatial search, and target-directed motor tracking (Fellows et al. 2017; Kopp et al., 2015; Perianez et al., 2007; Salthouse & Fristoe, 1995; Varjačić et al., 2018a). It is important to note, that there is a substantial correlation between TMT-A and TMT-B indicating that they capture similar functions (Tamez et al., 2011; Varjačić et al., 2018a). It has been suggested that TMT-B builds upon TMT-A by adding an additional demand on executive functions (particularly set-switching and divided attention) (Varjačić et al., 2018a).

Over the past few decades, numerous studies have contributed to improve the normative data of the TMT by increasing sample sizes and creating norms according to demographic variables, such as age or education (Perianez et al., 2007). In a clinical context, these norms can be used to assess individuals in order to detect the presence or absence of cognitive impairments. Additionally, comparisons of individuals within their clinical population can be made to understand the level of severity of the impairment. While some studies have examined the TMT performance in brain-damaged subjects (e.g. traumatic head injury, frontal lobe lesions, dementia) most normative studies have focused on non-clinical samples. Consequently, there is a shortage of research examining TMT performance in some clinical populations (Ashendorf et al., 2008; Kopp et al., 2015; Lange et al., 2005). In line with this, few researchers have examined the TMT performance of people that experienced a stroke (e.g Tamez et al., 2021). It should be noted that research on the neuropsychological performance of stroke survivors can give rise to methodological problems due to the heterogeneity of this population (Pambakian et al., 2004). Consequently, it is challenging to relate the performance of persons

that had a stroke to their reference group, as there is a scarcity of data describing usual or expected findings within this clinical population. Nevertheless, some authors have emphasized a general mental slowness in cognitive functioning in this group (Mahon et al., 2020; Winkens et al., 2006).

As far as we know, there have been no studies examining TMT performance in individuals that experience a post-stroke HH. Following this, the clinical utility of the TMT might be limited for this clinical population. That is to say, the TMT standard norms were developed without taking the possible effects of HH on this visual task into consideration. Consequently, it is difficult to interpret low TMT scores because poor test performance might reflect the visual defects of HH, as opposed to the cognitive abilities of the test-taker. When interpreting TMT performance of individuals with HH, clinicians might be faced with an elemental issue, namely to avoid inferring to a higher-order impairment, if impairments at a lower level might be present.

As previously mentioned, there is a gap of knowledge concerning the TMT performance of individuals that experienced a stroke and are suffering from HH. We undertook this study in order to investigate the clinical and diagnostic utility of the digitalized version of the TMT in persons diagnosed with HH. In light of the low recovery rates, gaining a better understanding of the visual disability and neuropsychological performance on the TMT is important. The aim of the current thesis is thus a preliminary attempt (1) to explore the TMT performance of stroke patients with HH in comparison to not only healthy controls, but also to people with acquired brain injuries without visual defects. The second aim of this research is (2) to assess whether the TMT performance differs for items located on the side of the blind versus intact hemifield in people with HH. In other words, a deeper look will be taken to relate the visual location of stimuli on the TMT and the type of HH to test performance.

Methods

Participants

For this study subjects from three different populations were examined. The demographic characteristics of participants are shown in Table 1.

Table 1

Group Descriptive

	HC		LHH		RHH		ABI w/o VFD	
Variables	N	%	N	%	N	%	N	%
Gender								
Male	90	39.1	22	55.0	16	57.1	20	71.4
Female	140	60.9	18	45.0	12	42.9	8	28.6
Total	230	100	40	100	28	100	28	100
Etiology								
Ischemic stroke	-	-	31	77.5	20	71.4	24	85.7
Hemorrhagic stroke	-	-	4	10.0	5	17.9	3	10.7
iCVA + hCVA	-	-	1	2.5	-	-	-	-
Stroke not specified	-	-	4	10.0	3	10.7	1	3.6
Education								
Low	14	6.1	12	30.0	5	17.9	8	28.6
Middle	64	27.8	17	42.5	14	50.0	11	39.3
High	151	65.7	11	27.5	9	32.1	9	32.1
Missing	1	0.4	-	-	-	-	-	-

Note. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects; iCVA = Ischemic stroke; hCVA = Hemorrhagic stroke.

Sixty-eight subjects with post-stroke HH were included in the study. The diagnostic instruments utilized were either the Humphrey Field analyzer perimeter or the Octopus perimeter. Importantly, all subjects experience a complete HH involving a loss of sight in the complete lower and upper half of the visual field. This initial sample was subdivided and subjects were

either classified as having left (n = 40) or right visual field (n = 28) defects. Individuals with hemianopic defects on the left had a mean age of 64 years (range: 36-81 years), while those with hemianopic defects on the right had a mean age of 59 years (range: 21-80 years). The study also included 28 patients with acquired brain injury without visual defects (ABI w/o VFD), with a mean age of 59 years (range: 46-87 years). Causes of HH and ABI w/o VFD included ischemic stroke, hemorrhagic stroke, combined etiology, or unknown etiology. For the ABI w/o VFD group, only participants with a visual acuity score of 0.8 or higher were included in the study to ensure their ability to distinguish letters and numbers on the TMT. It is important to note, that there is a lack of data on the visual complaints for 20 ABI w/o VFD subjects. For the remaining eight subjects, information about the general type of visual disorder experienced (such as disorders of the lens, disorders of the choroid and retina, disorders of the eye and adnexa, and disorders of the ocular muscles) and not about the corresponding ICD codes. All participants with HH and ABI w/o VFD were recruited from 18 different outpatient locations maintained by the Royal Dutch Visio. A total of 230 healthy controls were recruited at the University of Groningen, with a mean age of 55 (range: 21-86 years). The recruitment was carried out using various methods inclduing local newspaper advertisements, social media, library notices and personal referrals.

All participants included in this study were born in the Netherlands and are fluent Dutch speakers. The Dutch Verhage scale was utilized to classify their level of education (Verhage, 1964). Therefore, its categories were merged into three ordinal categories: low (finished primary education, primary education, and less than two years of low-level secondary education, or finished low-level education), middle (finished average level secondary education), and high (finished high-level secondary education, or university degree). Participant data was collected in accordance with the latest version of the Declaration of Helsinki con-

cerning ethical standards of research involving human subjects. The study was approved by the Medical Ethical Review Board of the University Medical Center Groningen. The healthy control study was approved by the ethical committee of psychology at the University of Groningen. Moreover, all subjects signed an informed consent form before participating in the study.

Materials, Assessment, and Measures

All participants were assessed with the DiaNAH Test Battery which is a digitized screening tool created to assess mid-level and higher-order visual perceptual disorders after ABI (de Vries et al., 2015). The DiaNAH Test Battery consists of 11 different visual perception tests and takes approximately 30-60 minutes to complete (Heutink et al., 2018). The composition of the battery is based on recommendations by a group of national and international experts in the field of visual perception that participated in a Delphi study (de Vries et al., 2018). Importantly, the present study focuses on the patient data on the dTMT which is included in the DiaNAH Test Battery.

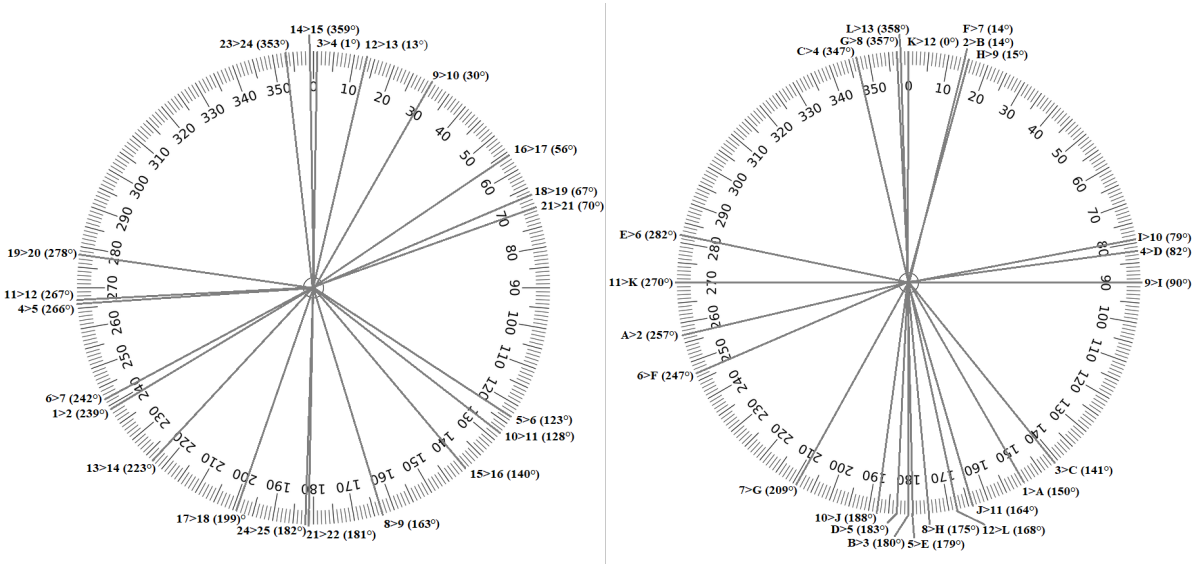
Since the present study included a digital version of the TMT, participants were required to complete the test with an electronic stylus pen on a Wacom 24.1-inch screen tablet (Cintiq 24 HD) equipped with the DiagnoseIS software program of Metrisquare B.V. The administration of the dTMT in this study followed the A4 format commonly adopted in the literature. In addition, the distribution of stimuli was identical to the traditional paper-pencil version of the TMT. The two parts of the TMT (Trail A and Trail B) involved connecting a total of 25 randomly distributed items in ascending order. On TMT-A encircled number stimuli from 1 to 25 were displayed, while on TMT-B participants had to connect number stimuli (1-13) alternating with letter stimuli (A-L). The time taken to complete the test was registered digitally from the first touch of the stylus pen on the screen until the last stimulus was

reached.

For our second aim to relate the side of HH and the location of the number or/ and letter stimuli to test performance, the diagonal magnitude of each stimulus in relation to the previous stimulus on the TMT was registered. A full circle was chosen to determine the exact diagonal magnitude of each stimulus to the next. To be more precise, stimuli were positioned in the center of a circle and their position in relation to the next stimulus was indicated by the exact angle measured in degrees. A visual presentation can be seen in Figure 1.

Figure 1

Diagonal magnitude of stimuli on TMT-A and TMT-B



Note. The diagonal magnitude of stimuli included on the TMT-A can be seen on the left, while the diagonal magnitude of stimuli included in TMT-B can bee seen on the right. The diagonal magnitude is measured in degrees.

As a next step, stimuli included in the TMT-A and TMT-B were grouped into two ca-

tegories based on the direction of the gaze shift required to detect them. Stimuli requiring a left-to-right gaze shift were included in the category Right, while the second stimulus set, which required a right-to-left gaze shift for detection, was designated as the Left category. We only considered stimuli with a minimum deviation of +/-30 degrees from the main axis (30-150 degrees for the Right category, 210-330 degrees for the Left category). That is because stimuli located outside these sections required participants to shift their gaze in a relatively upward or downward direction rather than to the left or right. The TMT-A Right category consisted of eight items (9>10, 16>17, 18>19, 20>21, 2>3, 5>6, 10>11, 15>16), while the TMT-A Left category included seven items (13>14, 1>2, 6>7, 4>5, 11>12, 19>20, 7>8). For the TMT-B Right category, there were five items (1>A, 3>C, 4>D, 9>I, I>10), while the TMT-B Left category included four items (6>F, A>2, 11>K, E>6).

As a next step, the time intervals to connect each stimulus with the next stimulus (referred to as inter-stimulus intervals) were reported. The dTMT permitted documentation of each inter-stimulus interval relevant to this analysis. It is worth noting that the included time intervals were corrected for distance, as stimuli varied in their distance from one another. More precisely the distance corrected stimulus variable was computed by dividing the inter-stimulus interval in second by the distance of the interval in cm.

Procedure

The instructions on how to complete the test were given orally by a researcher before completing trail A and again before completing trail B. Participants were instructed to connect the encircled stimuli in ascending order as fast and as accurately as possible with an electronic stylus pen. The tablet was placed at a 45-degree angle in front of the subjects. Additionally, participants got access to a shorter trial run (a shorter version of TMT-A and TMT-B) prior to the completion of trail A and trail B. The researchers verified that participants understood the

test instructions by asking if they were clear before the completion of each trial session. Trail A was presented first, followed by Trail B.

Statistical Analysis

The data was analyzed using IBM SPSS Statistics 28. Two distinct analyses were performed: one for the overall TMT performance and another to relate the visual location of test items and the side of the hemianopic visual field defect to dTMT performance. The sample was classified by diagnostic category: Healthy controls (HC), individuals with HH involving the right halves of the visual field (RHH), individuals with HH involving the left halves of the visual field (LHH), and individuals that had a stroke but did not experience HH (ABI w/o VFD).

For the first analysis, basic descriptive analysis was conducted to assess the mean of the total completion time on TMT-A and TMT-B for each diagnostic group. Due to violations of the homogeneity and normality assumption, a non-parametric test was chosen to evaluate significant differences between the diagnostic groups. The Kruskal-Wallis test was performed with the total completion time on TMT-A and TMT-B as the dependent variables, and the diagnostic groups as the independent variables. Afterwards, a pairwise comparison was conducted in order to detect which groups differed significantly from one another.

The second part of the analysis involved computing four new variables by summing up the inter-stimulus intervals for items included in (1) TMT-A Right, (2) TMT-A Left, (3) TMT-B Right and (4) TMT-B Left. These four variables represented time sum scores of the inter-stimulus intervals included in each category. Importantly, inter-stimulus intervals that were corrected for distance were included in the analysis. Descriptive statistics were employed to compare differences between sum scores between the four diagnostic groups. Additionally, sum scores for each variable were divided by the number of items included in that

variable. This calculation allowed to determine the average time score needed to detect items in each category.

A non-parametric analysis to test for significant differences was chosen due to violations of the homogeneity and normality assumption. To relate the visual location of test items and the side of the HH (e.g. left or right HH) to TMT performance, the Kruskal-Wallis test was performed. The four new variables, which were the sum scores of inter-stimulus intervals for each category of TMT-A and TMT-B, were the dependent variables, while the diagnostic group was the independent variable. Finally, a post-hoc pairwise comparison was conducted to determine which groups differed significantly from one another

Results

The subjects in the HC group completed the TMT-A the fastest (M = 31.01, SD = 10.58) followed by individuals with ABI w/o VFD (M = 50.61, SD = 30.67), individuals with RHH (M = 60.15, SD = 36.97), and individuals with LHH (M = 67.10, SD = 27.82). Further, the descriptive statistics show that a different order emerged for TMT-B performance. The HCs displayed the best TMT-B performance (M = 68.41, SD = 32.82) followed by individuals with ABI w/o VFD (M = 124.92, SD = 64.85), individuals with LHH (M = 159.27, SD = 104.85), and individuals with RHH (M = 166.10 , SD = 116.1).

Levenes's test of homogeneity revealed significant differences in variance for total completion time for TMT-A ($p < .001$) and TMT-B ($p < .001$). Additionally, the Shapiro-Wilk test was performed and showed evidence of non-normality for TMT-A ($p < .001$) and TMT-B ($p < .001$) total completion time for the four groups.

The Kruskal-Wallis test indicated that there was a statistically significant difference for the mean total time for completion on the TMT-A between the four different diagnostic groups ($H(3) = 98,232$, $p = < .001$). We conducted pairwise comparisons to reveal which dia-

gnostic groups differed significantly from each other. The p-values and adjusted p-values of the pairwise comparisons are presented in Table 2.

Table 2

Pairwise comparison TMT-A total time to completion

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
TMT-A TCT					
HC - ABI w/o VFD	-85.680	18.865	-4.542	< .001*	.000
HC - LHH	-135.562	16.146	-8.396	< .001*	.000
HC - RHH	-99.483	18.865	-5.273	< .001*	.000
ABI w/o VFD - LHH	49.882	23.224	2.148	.032*	.190
ABI w/o VFD - RHH	13.804	25.190	.548	.584	1.000
RHH - LHH	36.079	23.224	1.554	.120	.722

Note. Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects; TMT-A TCT = Trail making test A total time to completion.
Adj. Sig = Significance values have been adjusted by the Bonferroni correction.
*$p < .05$.

It can be seen that the mean for total time to completion on TMT-A of the HC group was significantly different from the RHH group, LHH group, and ABI w/o VFD group. No other significant differences between the groups were demonstrated. Additionally, the Kruskal-Wallis test revealed a statistically significant difference for the mean of total time for completion

on the TMT-B between the four diagnostic groups (H(3) = 102,410, p = < .001). The results of the pairwise comparison are presented in Table 3.

Table 3

Pairwise comparison TMT-B total time to completion

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
HC - ABI w/o VFD	-102.007	18.865	-5.407	< .001*	.000
HC - LHH	-124.547	16.146	-7.714	< .001*	.000
HC - RHH	-115.597	18.865	-6.128	< .001*	.000
ABI w/o VFD - LHH	22.539	23.224	.971	.332	1.000
ABI w/o VFD - RHH	13.589	25.190	.539	.590	1.000
RHH - LHH	8.950	23.224	.385	.700	1.000

*Note***.** Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects; TMT-B TCT = Trail making test B total time to completion.
Adj. Sig = Significance values have been adjusted by the Bonferroni correction.
**p < .05.*

The results of the pairwise comparisons indicated that the the HC group demonstrated a significantly different mean total time for test completion on TMT-B compared to the RHH group, LHH group, and ABI w/o VFD group. No other significant differences were observed between the groups.

TMT performance in relation to test item location on TMT

The the sum and mean scores for the detecting stimuli in the category Right and Left on TMT-A and TMT- B across the four diagnostic groups are displayed in Table 4.

Table 4

Sum and mean scores for the detection of items in the category Left and Right on the TMT

	HC		LHH		RHH		ABI w/o VFD	
	Sum S.	M	Sum S.	M	Sum S.	M	Sum S.	M
Stimuli location								
TMT-A								
Right	1.76	0.22	3.38	0.42	3.23	0.40	2.55	0.32
Left	1.16	0.17	2.61	0.37	2.16	0.30	1.89	0.27
TMT-B								
Right	2.14	0.43	4.22	0.84	5.36	1.10	4.08	0.82
Left	1.16	0.29	3.13	0.78	2.95	0.74	2.16	0.54

Note. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects; Sum S. = Sum score; TMT-A = Trail making test A; TMT-B = Trail making test B. The sum scores comprised the added inter-stimulus intervals for items grouped into the categories TMT-A Right, TMT-A Left, TMT-B Right, and TMT- B Left. The mean was calculated by dividing the sum scores by the number of items included in each category.

The results show that all four groups displayed smaller mean scores for detecting stimuli that required a gaze shift from right-to-left (category Left) on TMT-A and TMT-B compared to stimuli that required a gaze shift from left-to-right (category Right).

Test items that required a left-to-right gaze shift to be detected

Levenes's test of homogeneity revealed no equality of variance for the time sum scores requiring a left-to-right gaze shift on TMT-A ($p < .001$) and TMT-B ($p < .001$). Additionally, the Shapiro-Wilk test was performed and indicated non-normality for TMT-A ($p < .001$) and TMT-B ($p < .001$).

The Kruskal-Wallis test indicated statistically significant differences for detecting stimuli in the category Right on TMT-A ($H(3) = 48.25$, $p = < .001$). The p-values and adjusted significance for the pairwise comparison are shown in Table 5.

Table 5

Detection of TMT-A items included in the category Right

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
HC - ABI w/o VFD	-62.538	18.865	-3.315	< .001*	.005
HC - LHH	-90.324	16.147	-5.594	< .001*	.000
HC - RHH	-77.074	18.865	-4.086	< .001*	.000
ABI w/o VFD - LHH	27.786	23.224	1.196	.232	1.000
ABI w/o VFD - RHH	14.536	25.190	.577	.564	1.000
RHH - LHH	13.250	23.224	.571	.568	1.000

Note. Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects.

Adj. Sig = Significance values have been adjusted by the Bonferroni correction.

*$p < .05$.

The pairwise comparisons revealed significant differences between the HC group and the LHH group, RHH group, and ABI w/o VFD group. In addition to this, no other significant differences between the groups were found.

The Kruskal-Wallis test was repeated to investigate whether there is evidence for statistically significant differences for detecting stimuli in the Right category on TMT-B. This analysis showed significant differences between the four groups (H(3) = 71,13, p = < .001). The p-values and adjusted significance of the pairwise comparisons are presented in Table 6.

Table 6

Detection of TMT-B items included in the category Right

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
HC - ABI w/o VFD	-86.774	18.865	-4.600	< .001*	.000
HC - LHH	-90.299	16.147	-5.778	< .001*	.000
HC - RHH	-109.131	18.865	-5.785	< .001*	.000
ABI w/o VFD - LHH	6.525	23.224	.281	.779	1.000
ABI w/o VFD - RHH	22.357	25.190	.888	.375	1.000
RHH - LHH	-15.832	23.224	-.682	.495	1.000

Note. Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury without visual defects.

Adj. Sig = Significance values have been adjusted by the Bonferroni correction.

**p < .05.*

The pairwise comparison revealed that the HC group differed significantly from individuals with LHH, individuals with RHH, and individuals with ABI w/o (p= < .001). No other significant differences between the groups could be found.

Test items that required a right-to-left gaze shift to be detected

Levenes's test of homogeneity revealed no equality of variance for the time sum scores for stimuli included in the Left category on TMT-A (p < , 001) and TMT-B (p < , 001). Additionally, the Shapiro-Wilk Test was performed and showed evidence of non-normality for TMT-A (p < , 001) and TMT-B (p < , 001).

The Kurskal-Wallis test indicated that the time needed to detect stimuli in the Left category on TMT-A did differ significantly among the four groups (H(3) = 67,07, p = < .001). The results of the pairwise comparisons are shown in Table 7.

Table 7

Detection of TMT-A items included in the category Left

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
HC - ABI w/o VFD	-68.979	18.865	-3.656	< .001*	.002
HC - LHH	-116.668	16.147	-7.226	< .001*	.000
HC - RHH	-72.229	18.865	-3.829	< .001*	.001
ABI w/o VFD - LHH	47.689	23.224	2.053	.040*	.240
ABI w/o VFD - RHH	3.250	25.190	.129	.897	1.000
RHH - LHH	44.439	23.224	1.914	.056	.334

Note. Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury

without visual defects.

Adj. Sig = Significance values have been adjusted by the Bonferroni correction.

**p < .05.*

The pairwise comparison showed that the HCs differed significantly from individuals with LHH, individuals with RHH, and individuals with ABI w/o VFD. No other significant differences between the groups were found.

We conducted the Kruskal-Wallis test again to investigate if there are significant differences between the four groups for detecting stimuli on the left on TMT-B. The analysis indicated that there are significant differences between the groups (H(3) =85,068, p = < .001). The p-values of the pairwise comparison are presented in Table 8.

Table 8

Detection of TMT-B items included in the category Left

Sample 1 - Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
HC - ABI w/o VFD	-79.620	18.865	-4.220	< .001*	.000
HC - LHH	-124.494	16.147	-7.716	< .001*	.000
HC - RHH	-95.977	18.865	-5.088	< .001*	.000
ABI w/o VFD - LHH	44.975	23.224	1.937	.053	.317
ABI w/o VFD - RHH	16.3357	25.190	.649	.516	1.000
RHH - LHH	28.618	23.224	1.232	.218	1.000

Note. Each row tests the null hypothesis that sample 1 and sample 2 are the same. HC = Healthy controls; LHH = Individuals with left homonymous hemianopia; RHH = Individuals with right homonymous hemianopia; ABI w/o VFD = Individuals with acquired brain injury

without visual defects.

Adj. Sig = Significance values have been adjusted by the Bonferroni correction.

*$p < .05$.

It can be seen that the pairwise comparisons demonstrated that the HC group differed significantly from the LHH group, RHH group, and ABI w/o VFD group. No other significant differences between the groups were detected.

Discussion

The purpose of this study was twofold. Firstly, we examined the TMT performance of individuals suffering from post-stroke HH in comparison to individuals with ABI w/o VFD and neurologically healthy controls. Secondly, it sought to assess whether test performance differs for test items requiring a left-to-right versus right-to-left gaze shift for detection among subjects with HH, subjects with ABI w/o VFD and HCs. To the best of our knowledge, this is the first study not only evaluating the overall TMT-performance of subjects with HH but also providing an analysis of their TMT performance in relation to item location and visual defects.

At the level of overall TMT performance, the HC group needed significantly shorter periods of time to complete trail A and B of the TMT compared to the ABI w/o VFD, LHH and RHH group. These results are in agreement with prior research reporting that stroke is associated with worse cognitive functioning, mental slowness and worse performance on the TMT (Pihlaja et al., 2014, Tamez et al., 2011). Notably, a different order of ranks for total time to completion emerged for TMT-A and TMT-B. On TMT-A, subjects in the HC group displayed the best TMT-A performance followed by individuals with ABI w/o VFD, individuals with RHH, and individuals with LHH. On TMT-B, the HC group was the fastest to com-

plete TMT-B followed by individuals with ABI w/o VFD, individuals with LHH, and individuals with RHH. Previous findings of executive deficits in brain-injured subjects have suggested that particularly left hemispheric damage has been linked to poorer set switching (Miskin et al., 2016; Varjačić et al., 2018b). As mentioned earlier, TMT-B puts an additional demand on executive functioning. This might explain why individuals with RHH resulting from left-hemispheric damage performed worse on TMT-B compared to individuals with LHH.

Importantly, the analyses did not confirm any other significant differences between individuals with HH and individuals with ABI w/o VFD for total time to completion on TMT-A and TMT-B. One hypothesis explaining why no significant differences were found is that TMT-performance is mainly determined by post-stroke mental slowing rather than by the hemianopic visual loss. As mentioned previously, there is a lack of research comparing neuropsychological test performance of individuals that experienced a stroke with individuals experiencing additional post-stroke HH. So far, visual processing speed (VPS), the amount of time needed to make a correct interaction with a visual stimulus, of subjects with HH has been compared to HCs. In a study, Mena-Gracia and colleagues (2020) demonstrated that individuals with HH displayed slower VPS compared to HCs. Unfortunately, no comparison was made between subjects with HH and subjects with ABI w/o VFD. However, the hypothesis stated in the beginning of this paragraph is in contradiction with a body of literature suggesting that hemianopic defects are associated with significantly worse performance on a variety of tests relying on visual information (de Jong et al., 2016; Keller & Lefin-Rank, 2010; Mena-Garcia et al., 2020; Tant et al., 2002; Tant, 2002). Nevertheless, it should be noted that none of the cited studies included a comparison of individuals with ABI w/o VFD and individuals with post-stroke HH. It is important to consider that individuals with HH might be able to naturally compensate on visual scanning tasks, resulting in performance that is similar to

that of individuals with ABI who do not have VFD.

Zihl (2000) reported that in a proportion of individuals with HH saccadic accuracy, the ability to accurately move the eyes to one designated point to another, is preserved. More precisely, 42.1% of individuals with RHH and 32.4% of individuals with LHH displayed normal saccadic accuracy in the affected hemifield during a visual search task (Zihl, 2000). It is possible that a predominant proportion of individuals with HH included in this study exhibited normal saccadic accuracy despite their VFD. This may have lead to a better search performance, which is indicated by the absence of any significant differences in performance between the HH and ABI w/o VFD group.

The second analysis investigated whether there were any differences in test performance for items that require either a left-to-right or right-to-left gaze shift in order to be detected. The main objective of the second analysis was to elucidate how test performance differed for items located on the side of the blind versus intact hemifield in individuals with HH. One remarkable result to emerge from this analysis was that all four diagnostic groups were faster to detect stimuli in the category Left than stimuli in the category Right. It is interesting to note that individuals with LHH were faster in detecting stimuli in their blind hemifield than in their intact hemifield.

These results are in agreement with previous research reporting an asymmetry in visuospatial attention whereby stimuli located in the left hemifield are processed faster and more accurately in comparison to stimuli appearing in the right hemifield (Newman et al., 2017). Importantly, this left-sided preference of spatial attention has been related to right-hemispheric dominance for visuospatial attention processing and has been documented in neurologically healthy individuals and individuals with brain pathology (e.g. hemineglect) (Siman-Tov et al., 2007; Sosa et al., 2010). In line with this, Zihl (1995) has demonstrated that the

vast majority of individuals with RHH (87%) have a tendency to shift their gaze from a reference point to the left hemifield before they start exploring the right hemifield during a visual search task. In contrast, only half (48%) of the individuals with LHH in this study demonstrated this pattern of exploring the left hemifield first (Zihl 1995). It is still not entirely clear why the subjects with LHH included in this study needed longer to detect stimuli in the unaffected hemifield compared to their blind hemifield. There may have been an overrepresentation of individuals with LHH displaying an unconscious left-sided preference included in this study. Alternatively, it might be that these individuals exhibit a high level of awareness with respect to their visual field loss. Consequently, they might engage in overcompensation by shifting their gaze more towards the affected hemifield which might lead to shorter search times for items located on the left compared to items located on the right.

Another result to emerge from the analysis was that the HC group was significantly faster in detecting stimuli included in the category Right and Left on both TMT-A and TMT-B compared to the LHH, RHH and ABI w/o VFD group. These findings are consistent with previous research demonstrating that HCs outperform individuals that experienced a stroke, both with and without visual loss, on visual search tasks (Beasley & Davis, 2013; Pihalaja et al., 2014). Contrary to expectations, no other significant differences were found between the groups. It is surprising to note that there were no statistically significant differences between individuals with ABI w/o VFD and individuals with LHH in detecting stimuli included in the category Left on both test conditions. In addition, no differences were found between individuals with RHH and individuals with ABI w/o VFD for stimuli included in the category Right on both test conditions. Once again, it seems plausible that the HH population may have included a disproportionate number of subjects compensating effectively for their visual field loss. As a result, these subjects might have directed their gaze more frequently towards their

blind hemifield. This might have contributed to the absence of significant differences in search times between individuals with HH and individuals with ABI w/o VFD. In line with this, previous research has demonstrated that individuals with HH exhibit compensatory visual behaviors, including the tendency to concentrate their gaze more frequently towards their blind hemifield when viewing simple patterns (Pambakian et al., 2004). According to the authors, this strategy is employed to increase visual information acquisition by bringing more of a visual scene into seeing (Pambakian et al., 2004). This compensatory mechanism may explain why no significant differences between the HH group and subjects with Abi w/o VFD were observed.

Limitations

Several limitations of the present investigation should be mentioned. A major shortcoming limiting the generalizability of the results is the incomplete data regarding the visual problems in the ABI w/o VFD group. Given that these individuals were sampled at an expertise center for visually impaired and blind people, it is reasonable to assume that all ABI subjects were afflicted with some degree of visual impairment. Unfortunately, only general disease information for a mere eight subjects in the ABI w/o VFD group is known (e.g. disorders of the lens, disorders of choroid and retina, diseases of the eye and adnexa, and disorders of the ocular muscles). That is to say the specific diagnoses of the visual impairment (e.g. cataracts) remains unknown. Apart from this, there is no information regarding visual impairments for the majority of the ABI w/o VFD sample. Given the limited data available, it is only possible to rule out the presence of HH. It is thus necessary to consider that they might experience one or more of the other visual anomalies outlined above. As a result, we cannot exclude methodological problems due to the possible heterogeneity of the ABI w/o VFD group.

Apart from this, it needs to be noted that there is a considerable proportion of stroke

patients that do not experience any visual difficulties following a stroke (Hepworth, 2016). To be more specific, Hepworth and colleagues (2016) estimated that 35% of stroke survivors do not experience any post-stroke visual impairments. Since our ABI w/o VFD sample does not include individuals without visual impairments, the absence of these individuals might limit the generalizability of our findings. It could be postulated that participants in our ABI w/o VFD sample may demonstrate inferior TMT performance relative to the overall population of stroke survivors who typically experience fewer visual difficulties. Additionally, it can be hypothesized that the TMT performance of our visually impaired ABI w/o VFD sample may be worse than the TMT performance of the general ABI population. Therefore, the TMT performance of our visually impaired ABI w/o VFD sample might be more similar to the TMT performance of individuals with HH. This conjecture finds support in the literature, as some authors have highlighted that visual impairments are associated with lower test scores on neuropsychological assessments involving vision (de Haan et al., 2019; Kempen et al., 1994). It should be noted that this factor might partially account for the lack of significant differences between the HH and ABI w/o VFD sample in our study.

In addition, the results in this study are based on performance of healthy Dutch participants recruited through convenience sampling. A well-known disadvantage of this method concerns the risk that the sample might not be representative for the larger Dutch population. Importantly, a relatively small number of individuals with a lower education (6,5 % compared with 35 % in the general Dutch population) (CBS Statistics Netherlands, 2023) was included in the HC group. Hence, it is important to consider that the test scores for the TMT among HCs in this study may reflect the typical performance of individuals with a higher education rather than the performance of the general Dutch population. The mean completion times for TMT-A (31.01) and TMT-B (68.41) of HCS observed in our study are consistent with those

reported by Tombaugh (2004), who developed norms specifically for individuals with higher levels of education (Age = 55-59; education = 12+ years; TMT-A: 31.72; TMT-B: 68.74).

A key aspect to remember is that the present study employed a non-matched sample which has resulted in notable differences in demographic characteristics across the groups. Specifically, the HCs did not only present with the highest mean for educational status but also with the lowest mean age (55 years), while individuals with LHH presented with the lowest mean for educational status and highest mean age (64 years). Additionally the RHH and ABI w/oVFD group presented with comparable levels of education and identical mean ages (59 years). It is worth noting that prior research demonstrated that age and education have a statistically significant effect on the TMT performance (Abi Chahine et al., 2019; Tom-baugh, 2004; Woods et al., 2015). Additionally, Makin and colleagues (2018) point out that this also applies to stroke patients since they found evidence that pre-morbid IQ is a strong predictor for post-stroke cognition. Higher age has been identified as a main factor lea-ding to worse test results (Tombaugh, 2004). To be more precise, TMT-A completion times have demonstrated age slopes ranging from 0.2 s/year to 0.6 s/year, while TMT-B completion times have demonstrated age slopes ranging from 0.6 s/year to 1.6 s/year (Tombaugh, 2004; Woods et al., 2015). Lower levels of education have also been linked to worse TMT performance, although its effect is weaker compared to age (Woods et al., 2015). Steinberg and colleagues (2005) found that differences on TMT-B completion times between participants with a college education and elementary school is similar to that associated with a 10 year age difference. Following the evidence presented above, the lower TMT performance of the HH and ABI w/o VFD group in comparison to the HC group may be partially attributed to differences in age and educational status. Following this, caution should be exercised when interpreting our re-

sults as the effects of demographic characteristics on TMT performance were not controlled for.

Conclusion and Future Directions

In clinical practice strokes are commonplace and are projected to become more prevalent with the aging population. HH is a debilitating consequence of stroke that can lead to functional disability, and its effects can negatively influence rehabilitation and quality of life. Given the persistent burden and the lasting impact of HH, research investigating the VFD and neuropsychological test performance of individuals with HH is crucial for improving our understanding of this condition. However, conducting research with individuals suffering from HH is a challenging task due to the heterogeneity within the population of stroke survivors. Despite the significance of this issue, research in the area of neuropsychological test performance of HH patients is notable by its absence.

We have presented a preliminary attempt to investigate TMT performance of individuals with HH, along with exploring the relationship between the visual location of stimuli on the TMT and the side of hemianopic defects to TMT performance. Our results revealed that subjects with HH displayed a significantly worse TMT-A and TMT-B performance than HCs. Moreover, our expectations were confirmed as subjects with HH required significantly longer search times to detect stimuli located in both the left and right hemifields compared to HCs. Another significant difference was observed in the completion times of TMT-A and TMT-B between HCs and individuals with ABI w/o VFD. HCs demonstrated faster completion times for both test conditions and were quicker compared to individuals with ABI w/o VFD in detecting test stimuli requiring both a left-to-right and right-to-left gaze shift. Against expectations, our results revealed no other significant differences between the HH and ABI w/o VFD

groups. This raises the possibility that post-stroke mental slowing may have a greater influence on TMT performance than the hemianopic visual defects.

Due to the limited number of subjects and the presence of multiple methodological limitations in the study design, caution should be exercised when interpreting the results of this analysis. Despite the limitations of this study, we believe that our work could be the stepping stone for further research. Given the heterogeneity of the stroke population, research into their neuropsychological performance is a difficult task, fraught with methodological problems. Therefore, future research should adopt very careful sampling techniques. In addition, to increase the generalizability of results, future investigations should be based on bigger sample sizes.

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