Summer 2023

Predictors of Driving Performance Post-Stroke

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PREDICTORS OF DRIVING PERFORMANCE POST-STROKE

by

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Bachelor of Science Degree
Augusta University, 2021

Submitted in Partial Fulfillment of the Requirements

For the Degree of Master of Science in

Exercise Science

Arnold School of Public Health

University of South Carolina

2023

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Abstract

Driving is a complex skill involving the interaction of various brain functions, making it challenging to determine the independent contributions of each process to driving proficiency. While past studies have identified assessments such as the Useful Field of View Test (UFOV) and the Trial Making Test (TMT) as strong predictors for driving skills, little research has explored the impact of visual search and movement inhibition on driving after stroke. This cross-sectional study includes participants between the ages of 21 to 80 years with residual disability caused by a unilateral middle cerebral artery stroke at least six months prior. The participants undergo various visuomotor and functional object detection tasks using the KINARM with EyeLink 1000. Bivariate regression analysis is employed to identify relevant predictor measures related to driving proficiency. Subsequently, multiple regression models are used to determine which predictor measures independently predict driving performance post-stroke. The results indicate that measures of eye fixations and distractors avoided show the strongest association with driving performance, supporting the hypothesis that visual search and movement inhibition abilities are significant predictors of driving after stroke. Further exploration of the relationship between these predictor measures and their potential ability to enhance the understanding of driving impairments post-stroke.

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List of Abbreviations

BIC .... Bayesian Information Criteria

BLD .... Brake Lights Detected

DS .... Driving Score

FOD .... Functional Object Detected

KINARM .... Kinesiological Instrument for Normal and Altered ReachingMovements

MATLAB .... Matrix Laboratory

OHA .... Object Hit and Avoid

SD .... Speed Difference

TD .... Targets Detected

TMT .... Trial Making Test

UFOV .... Useful Field Of View

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Chapter 1: BACKGROUND

1. Psychomotor Basis of Driving

Driving is a complex multifaceted skill in which many brain functions must efficiently interact to continuously and simultaneously gather and process information, make decisions, and perform movements. *Sensory processes* gather information from the environment, *perceptual processes* determine the identity and location of information, *cognitive processes* (executive functions) integrate information with prior knowledge to select appropriate actions, and *motor processes* execute movements used to control how a vehicle moves relative to the environment. Importantly, proficient driving often requires complex interactions between sensory, perceptual, cognitive, and motor processes. For example, various sensory, perceptual, cognitive, and motor processes interact to select, organize, and execute sequences of eye movements (visual search) used to gather visual information from the environment. Given the number of distinct processes that underlie driving, post-stroke impairments affecting many processes may negatively affect driving performance. However, the complex interactions between the different brain processes makes it difficult to determine their independent contributions to driving performance.

1.2 Relationships Between Driving and Visual Perception

Visual perception refers to the ability to process and interpret visual information, such as the shape, color, location, and motion of visual stimuli. The ability to identify visual stimuli largely depends on high-resolution visual processing within the central

(foveal) region of the retina (Marsden et al., 2014). In contrast, the ability to locate visual stimuli mainly depends on low-resolution visual processing within the peripheral retina (Marsden et al., 2014).

1.2.1 Visual Acuity and Peripheral Vision

Tests of visual acuity and peripheral vision are commonly included as part of driver licensing standards (Wood et al., 2021). Driving depends on central vision to identify objects like brake lights, turn signals, signs, and traffic lights. Tests of visual acuity such as Snellen charts, which measure the ability to correctly identify different-sized letters or numbers, assess the ability to use foveal vision to correctly identify visual stimuli. Driving also relies on peripheral vision to provides information about where objects are located and how they are moving. Tests of peripheral vision assess the ability to detect visual stimuli presented peripherally.

Surprisingly, a study of vision and driving found that vision was only weakly related to motor vehicle accidents or driving risk except in drivers with significantly reduced visual acuity or substantive loss of peripheral vision (Dickerson et al., 2014). This was supported by recent systematic review, which confirmed that low visual acuity and loss of peripheral vision diminish driving performance (Wood et al., 2021).

1.2.2 Visual Processing Speed and Accuracy

While visual acuity and peripheral vision are important, we know that speed and accuracy of visual processing also contribute to driving performance. Visual processing speed refers to the amount of time needed to determine the identify or location of visual stimuli. Visual processing accuracy refers to how often individuals can correctly determine the identify or location of visual stimuli within a given amount of time. There

is strong evidence that visual processing speed and accuracy are important contributors to driving proficiency. Notably, an intervention designed to increase the speed and accuracy of visual processing led to a significant reduction in the rate of at-fault motor vehicle accidents (Golisz, 2014). A systematic review also confirmed that visual processing speed contributes to driving performance (Egeto et al., 2019).

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1.2.3 Visuospatial Awareness

Central and peripheral vision are also needed for visuospatial awareness, which refers to our awareness of what objects are present and where they are located within the surrounding environment (Endsley, 1988; Smith and Hancock, 1995 as cited in Wolfe et al., 2017). Visuospatial awareness is important for proficient driving because it facilitates quick and accurate decisions in response to the current environment and helps drivers to

anticipate decisions that they will need to make in the future (Gugerty, 2011 as cited in Wolfe et al., 2017).

1.2.4 Visual Attention

Attention broadly refers to our ability to focus or concentrate on specific information. Attention facilitates visual processing by allocating attention to where relevant information is located (spatial attention) and when it is present (temporal attention). The ability to efficiently shift attention to relevant information located at different places over time is characteristic a of good visual attention.

Several studies have investigated relationships between visual attention and driving performance. Impairments of visual attention are associated with longer and more variable braking times (Lodha et al. 2021), and impaired visual attention is well established as a good predictor of poor driving after stroke (Mazer et al., 2001). Experimental studies have also shown that interventions designed to improve visual attention enhance the speed and accuracy of visual processing leading to better driving proficiency (Owsley et al., 2013). In addition, the findings of these studies were supported by a recent systematic review, which found that visual attention is an important contributor to proficient driving (Egeto et al., 2019).

1.3 Relationships Between Driving and Executive Function

Executive functions are a subset of cognitive processes that allow us to flexibly select, organize, and modify behaviors during novel situations (Heshmatollah Ghawami et al. 2022). Individuals with executive dysfunction often exhibit impaired planning, decision-making, and task-switching (Motto et al., 2014; Elliot, 2003). Executive functions such as working memory, inhibitory control, and self-monitoring are normally

used during driving to select, organize, and modify movements used to navigate vehicles through the environment (Demnitz et al. 2016). Studies of driving after stroke have consistently found that impairments affecting executive functions negatively impact driving proficiency, particularly in complex, novel, and unpredictable environments (Gillen & Rubio, 2011 as cited in Motta et al., 2014). However, to our knowledge, no previous studies have examined how driving performance is affected by diminished inhibitory control after stroke.

1.4 Visual Search & Information Processing

Visual search refers to organized sequences of saccades (rapid eye movements) and fixations (stationary periods) that move the fovea to gather information from visual stimuli. Previous studies of visuomotor performance after stroke found that deficits in working memory and spatial planning underlie impaired visual search (Singh et al., 2017), which was subsequently associated with inefficient information processing, diminished control of reaching movements, and difficulties with hand function and gait (Singh et al., 2018).

1.4.1 Relationships Between Driving and Motor Function

Although proficient driving depends on the ability to precisely manipulate the steering wheel and pedals, surprisingly few studies have investigated relationships between driving performance and motor function. A study of healthy older adults found that diminished control of ankle movements was associated with poor reactive driving (Lodha et al. 2016). A subsequent study showed that stroke survivors with decreased control of ankle movements were more likely to exceed the speed limit and had greater difficulty adapting their speed and maintaining safe trailing distances (Lodha et al. 2021).

This study also found that a combination of cognitive and motor impairments, rather than cognitive impairments alone, contributed to longer and more variable delays before braking.

In addition to the ability to execute movements, many motor skills require the ability to inhibit movements, which is regulated by inhibitory control, an important executive function. Like other motor skills, proficient driving also depends on the ability to inhibit movements. For example, during a lane change, if another vehicle unexpectedly moves into the adjacent lane, drivers must be able to inhibit movements used to turn the steering wheel. Although the ability to inhibit movements is crucial for driving, to our knowledge, no previous studies have examined the relationship between driving performance and movement inhibition after stroke.

1.5 Specific Aims and Hypothesis

The proposed research will investigate two key knowledge gaps highlighted above. First, the extent to which diminished driving performance after stroke is associated with impairments of visual search is unknown. Second, the extent to which diminished driving performance after stroke is associated with impairments of movement inhibition is unknown. To investigate these knowledge gaps, the proposed research will address the following specific aims and hypotheses:

Specific Aim 1: Quantify the extent to which measures of visual search predict driving performance after stroke.

Hypothesis 1: Measures of visual search will predict driving performance after stroke independent of other predictors.

Specific Aim 2: Quantify the extent to which measures of movement inhibition predict driving performance after stroke.

Hypothesis 2: Measures of movement inhibition will predict driving performance after stroke independent of other predictors.

Chapter 2: METHODS

2.1 Study Design

The study used a cross-sectional design to address the specific aims and hypotheses identified above. Data examined in the study were previously collected between 2017 and 2020.

2.2 Subjects

The study included males and females from 21 to 80 years old who reported residual disability caused by a unilateral stroke of their middle cerebral artery at least six months earlier. Subjects were excluded if they have any of the following issues:

1. History of a neurological disorder other than stroke
2. Peripheral neurological or musculoskeletal issue of either arm or hand
3. An oculomotor issue that prevents eye tracker calibration
4. Visual impairment that cannot be corrected with lenses (Optec vision screener)
5. Moderate to severe cognitive impairment (Visual Cognitive Assessment score < 12)
6. Moderate to severe upper-limb motor impairment (Fugl-Meyer Motor Scale < 16)
7. Moderate to severe spasticity of either elbow (Modified Ashworth Scale > 2)
8. Visuospatial neglect (Behavioral Inattention Test score < 130)
9. Severe upper-limb apraxia (TULIA score < 5)

2.3 Assessments

After providing informed consent, all eligible subjects completed assessments of driving proficiency, visuomotor performance, and visual processing speed.

2.3.1 Assessments of Driving Proficiency

Driving assessments were carried out on a CDS-250 driving simulator (DriveSafety, Murray, UT). Subjects sat in a partial Ford Focus Cab that included a steering wheel, accelerator, brake, and speedometer (Figure 1A). Subjects used the controls to drive through virtual scenarios. Before completing the driving assessment, subjects completed two familiarization tasks, Lane Keeping and Pedals/Stopping, until they indicated that they were comfortable with driving the vehicle.

Functional Object Detection: Subjects completed three trials of a Functional Object Detection (FOD) task designed to assesses visuospatial awareness during driving. Subjects drove down a road and scanned for visual targets (letter “E”) randomly displayed at 28 locations from the left to the right (Figure 2.1). They were instructed to press a button on the steering wheel each time they saw a target, press the brake pedal each time they saw the brake lights of the lead car turn on, and maintain the speed of the vehicle at a target speed of 45 mph.

2.3.2 Assessment of Visuomotor Performance

Visuomotor assessments were conducted using a KINARM endpoint robot (KINARM, Kingston, ON) integrated with an EyeLink 1000 remote eye tracker (SR Research, Ottawa, ON) (Figure 2A). Subjects sat in a custom chair and grasped two handles to perform visuomotor tasks that involved making reaching movements in the horizontal plane to interact with visual targets presented in the same plane as their hands.

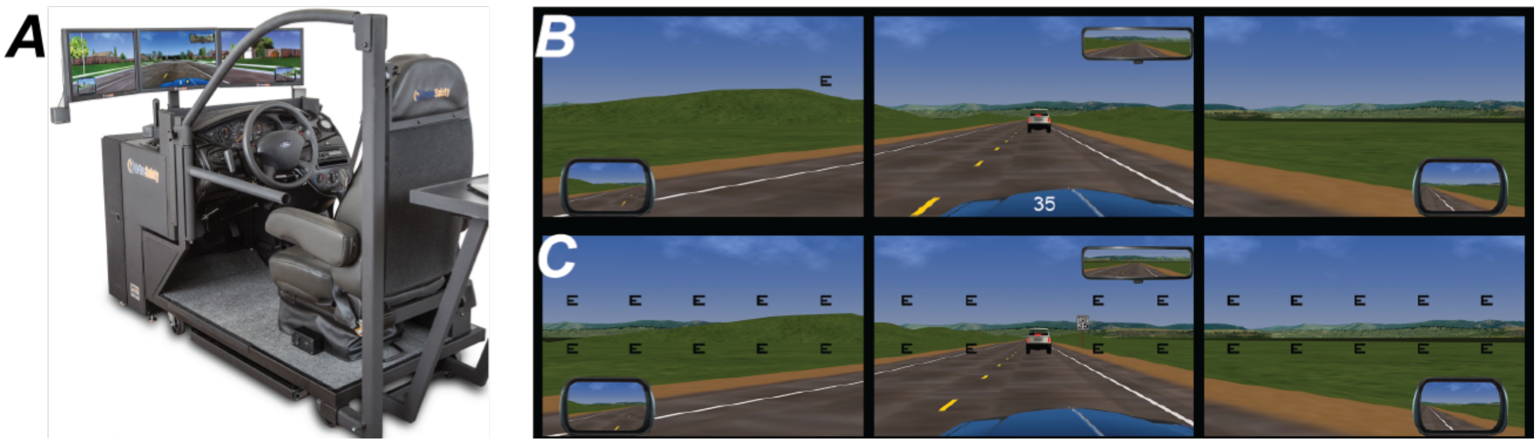

Figure 2.1: Driving simulator and Functional Object Detection (FOD) task. (A) Subjects sat in partial Ford Focus cab and used standard controls (accelerator, brake, steering wheel) to drive through virtual scenarios. (B) In the FOD task, subjects drove down a road and scanned the visual scene for targets (letter “E”) while concurrently watching break lights. (C) Targets appeared at 28 different locations on the subjects’ right and left.

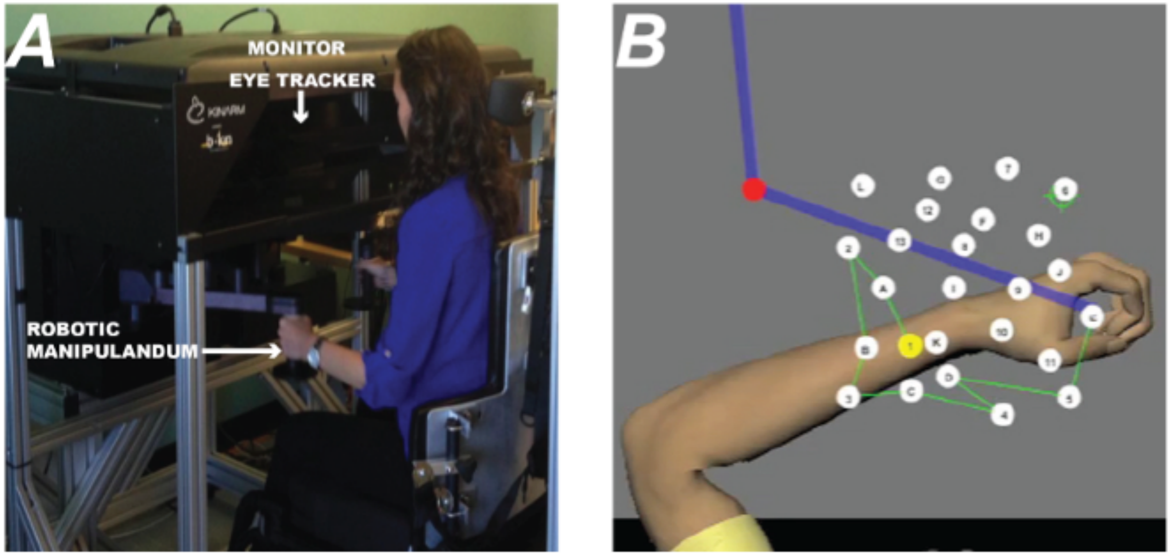

Figure 2.2: KINARM robot and Trail Making Test (TMT). (A) The KINARM robot included a custom chair, two handles (robotic manipulanda), an EyeLink 1000 remote eye tracker, and an augmented reality workspace in which a moniter could present visual targets in the same plane as the handles. (B) Alphanumeric TMT task (TMT-B), in which subjects moved their preferred hand to connect 25 targets, alternating between numbers and letters in sequential order.

Trail-Making Tests: The Trail Making Tests (TMT) are classical neuropsychological assessments of visual processing speed and executive function that are good predictors of driving proficiency. Subjects used the robotic device to complete the numeric and alphanumeric variants of TMT (Figure 2B). In the numeric variant (TMT-A), 25 visual targets (Numbers 1-25) were simultaneously presented at different locations in the horizontal plane. Subjects were instructed to move their preferred hand to draw lines connecting the numbers in sequential order. In the alphanumeric variant (TMT-B), 25 visual targets (Numbers 1-13, Letters A-L) were simultaneously presented at different locations in the horizontal plane, and subjects were instructed to move their preferred hand to draw lines alternating between numbers and letters in sequential order. Due to switching between number and letters, TMT-B has greater demands on executive functions involved in task switching.

Object Hit and Avoid: The Object Hit and Avoid (OHA) task is a continuous variant of the Go/No-Go tasks, which are classical neuropsychological assessments of visual processing speed and inhibitory control. Individuals are instructed to execute movements (e.g., button-press) in response to “go” stimuli and inhibit movements in response to “no-go” stimuli (Falconer et al., 2008, 2013; Korgaonkar et al., 2012). Individuals with good inhibitory control normally inhibit movements on “no-go” trials, whereas individuals with poor inhibitory control often execute erroneous movements on “no-go” trials. In OHA, 300 objects comprised of eight geometric shapes moved in the horizontal plane toward the subjects, who are instructed to move their hands to hit away two Target shapes (e.g., circle and rectangle; n = 200) and avoid hitting six Distractor shapes (e.g., square, triangle, oval; n = 100) with virtual paddles above each handle

(Figure 3B). Task difficulty increased over time by slowly increasing the number of concurrent objects and the speed that the objects moved toward the subjects. When a Target was hit, subjects felt haptic feedback from the handle and saw the Target move away. When a Distractor is hit, it passed through the paddle without any haptic feedback.

2.3.3 Assessment of Visual Processing Speed

Visual processing speed was assessed using the Useful Field of View (UFOV) tasks (Figure 4), which are good predictors of on-road driving ability (Wood et al., 2014). The UFOV tasks assess visual processing speed by measuring how long it takes to detect and localize visual targets under conditions of divided and selective attention. Subjects sat at a constant distance from a monitor and pressed keys on a keyboard to indicate the identity and location of vehicle (car or truck) presented on the monitor.

Divided Attention Task: The Divided Attention Task is the second subtest of the UFOV assessment. While looking at a central target, subjects indicated the identity and location of a target vehicle presented in the periphery (Figure 4A). When a subject's cumulative response accuracy was greater (less) than 78%, the amount of time the vehicle was present was decreased (increased) to obtain an estimate of the minimum amount of time that the vehicle needed to be present for the subject to respond correctly.

Selective Attention Task: The Selective Attention Task is the third subtest of the UFOV assessment. It was the same as the divided attention task, except the target vehicle was embedded in an array of peripheral distractors (i.e., triangles) (Figure 4 B). When a subject's cumulative response accuracy was greater (less) than 78%, the amount of time the vehicle was present was decreased (increased) to obtain an estimate of the minimum amount of time that the vehicle needed to be present for the subject to respond correctly.

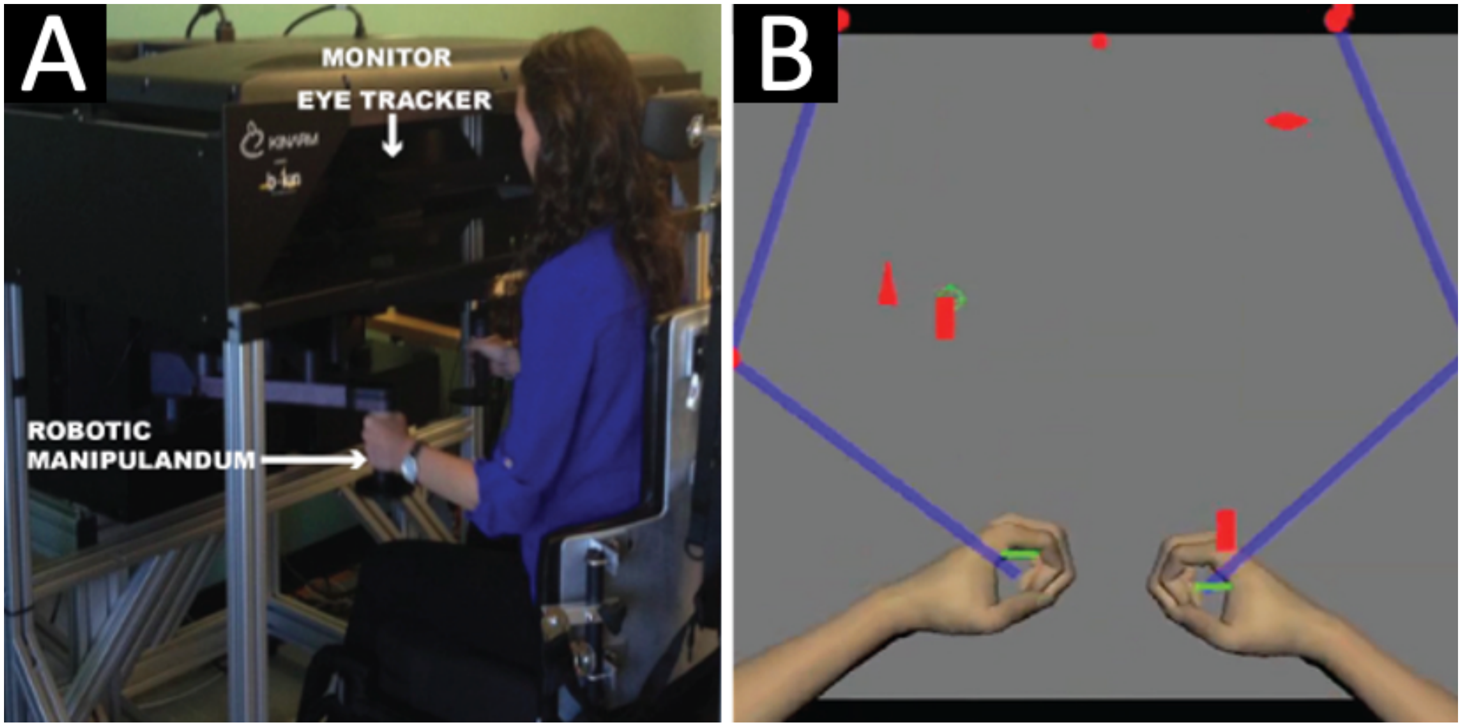

Figure 2.3: KINARM & OHA. (A) Participants were placed infront of the KINARM apporatus where the eye tracker, EyeLink 1000, was calibrated and measured visual search and hand movements for visuomotor performance. (B) Visuomotor task OHA assesses visual search during a bimanual task. Eight geometric shapes move towards the subjects as they use virtual paddles to hit away two targets and avoid the other six distractors.

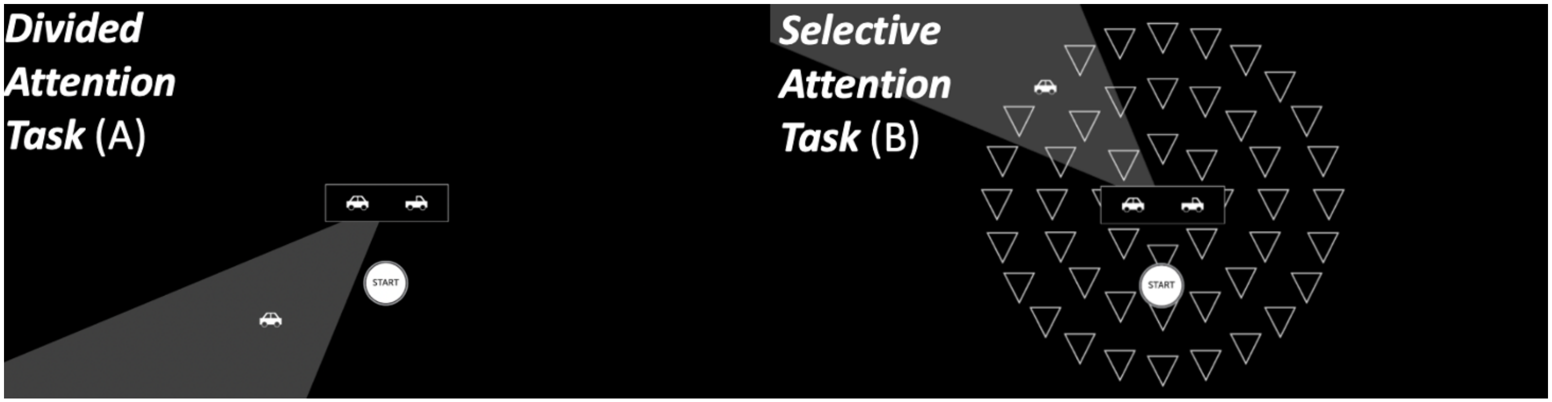

Figure 2.4: UFOV Tasks. UFOV reflects visual deficits that can measure visual processing for both rapid detection and localization of targets highlighting visuospatial attention and executive demands. Participants are tasked to give a non-speeded response identifying the object that was presented briefly at the center of the screen (i.e., car or truck) by clicking left or right. (A) Divided attention task assesses is a concurrent task of identifying the location of the vehicle in the periphery. (B) Selected attention is the same concurrent task with the addition of distractors (i.e., triangles) in the periphery.

2.4 Outcome and Predictor Measures

2.4.1 Measure of Driving Performance

Driving Score: A composite Driving Score from the FOD task was used as the primary outcome measure in the analyses. It was calculated as the weighted mean of three z-scores computed from targets detected (TD), brake lights detected (BLD), and speed difference from target speed (SD).

$$z_{TD} = z\left(\frac{\sum Targets\ Detected}{N_{\ Targets}}\right)$$

$$z_{BLD} = z\left(\frac{\sum Brake\ Lights\ Detected}{N_{Brake\ Lights}}\right)$$

$$z_{SD} = z\left(\frac{|\overline{Speed_{Vehicle}} - 45\ mph|}{45\ mph}\right)$$

$$Driving\ Score = \frac{z_{TD} + z_{BLD} + z_{SD}}{3}$$

2.4.2 Measure of Movement Inhibition

Distractors Avoided: Percent of Distractors Avoided during OHA was used as a predictor measure related to movement inhibition. If a distractor traversed the workspace without being touched by either paddle, it is counted as a “Distractor Avoided”.

$$Distractors\ Avoided = \frac{N_{Distractors\ Not\ Hit}}{100\ Distractors} * 100\%$$

2.4.3 Measures of Visual Search

Total Fixations: Total Fixations during TMT-A was used as predictor measure related to visual search. Total Fixations was calculated as the sum of all “Fixations” on a target that lasted at least 40ms, and included all fixations associated with correct movements from when the hand touched the first target until it touched the final target.

$$Total\ Fixations = \sum_{1}^{i} N\ Fixations_i$$

Objects Pursued: Percent of different Objects Foveated during OHA was also used as a predictor measure related to visual search. Objects Foveated is related to speed and efficiency of visual search and was calculated as the percent of all 300 objects that participants "foveated" at least once using pursuit eye movements. An object was counted as "Foveated" if it was pursued using foveal vision for at least 40ms [41]. Objects that were foveated more than once were only counted one time.

$$Objects\ Foveated = \frac{N_{Objects\ Foveated}}{300_{Objects}} * 100\%$$

2.4.4 Measures of Visuomotor Performance

Total Time: Total Time to complete TMT-A was used as a predictor measure related to overall visuomotor performance. Total Time was calculated as the total amount of time from when the hand touched the first target until it touched the final target. Since subjects make variable numbers of errors (i.e., reach to incorrect targets), only the time associated with correct movements were used to calculate Total Time.

$$Total\ Time\ (s) = \sum_{1}^{i} Time_i$$

Targets Hit: Percent of Targets Hit during OHA was used as a predictor measure related to overall visuomotor performance. Paddle-contact with a target was counted as a "Target Hit" if the contact caused the target to move away from the subject. If a target was hit away more than once, only one instance was counted as a "Target Hit".

$$Targets\ Hit = \frac{N_{Targets\ Hit}}{200\ Targets} * 100\%$$

2.4.5 Measures of Movement Execution

Speed Peaks: Average number of Speed Peaks during correct movements in TMT-A was used as a predictor measure related to movement execution, specifically

movement smoothness. Hand-speed during reaching movements normally exhibits a smooth profile with a single peak. After stroke, hand-speeds are often characterized by irregular profiles with multiple peaks. Speed Peaks was calculated as the average number of peaks in hand-speed during correct reaching movements.

$$Speed\ Peaks = \frac{\sum_{1}^{N} Speed\ Peaks_{Correct\ Movement}}{N_{Correct\ Movements}} \tag{2}$$

Hand-Speed Bias: Inter-limb differences in hand-speed (Hand-Speed Bias) during OHA were also used as a predictor measure related to movement execution. The right and left arms normally exhibit similar hand-speeds during reaching movements in OHA. After stroke, however, the contralesional (more-affected) arm often moves slower than the ipsilesional (less-affected) arm. Hand-Speed Bias was calculated as the relative differences in average hand-speed of the contralesional and ipsilesional hands.

$$Hand\text{–}\ Speed\ Bias = \frac{\overline{Hand\text{–}Speed_{Contra}} - \overline{Hand\text{–}Speed_{Ipsi}}}{\overline{Hand\text{–}Speed_{Contra}} + \overline{Hand\text{–}Speed_{Ipsi}}}$$

2.4.6 Measure of Task-Switching

Time Difference: The difference in time needed to complete TMT-A and TMT-B (Time Difference) was used as a predictor measure related to task switching. Time Difference is a good predictor of driving proficiency and was calculated as the difference between the Total Times in TMT-A and TMT-B.

$$Time\ Difference\ (s) = Total\ Time_{TMT-B} - Total\ Time_{TMT-A}$$

2.4.7 Measure of Visual Processing Speed

Divided Attention Speed: Divided Attention Speed was used as a predictor measure related to visual processing speed. It was the minimum presentation duration that subjects needed to correctly identify and locate peripheral targets in the Divided Attention Task.

Selective Attention Speed: Selective Attention Speed was also utilized as a predictor measure related to visual processing speed. It was the minimum presentation duration that subjects needed to correctly identify and locate peripheral targets in the Selective Attention Task.

2.5 Statistical Analyses

All analyses were performed using MATLAB (Mathworks Inc. Natick, MA), Bivariate regression was first used to identify measures related to Driving Scores. Predictors with a medium effect size ($f^2 \geq 0.15$) were identified as candidate predictor measures for subsequent multivariate analyses. In order to prevent multicollinearity from negatively affecting the multivariate analyses, each pair of candidate predictor measures with a high correlation ($r \geq 0.0707$) was identified and only the measure that had the strongest relationship with Driving Score was included in the multivariate analyses. Multiple regression and stepwise regression were then performed using the final set of predictor measures. Finally, semipartial coefficients of determination (sr^2), effect sizes (sf^2), and p-values (sp) were computed to identify measures that were independently predictive of Driving Scores ($sf^2 \geq 0.15$).

2.5.1 Sample Size

Based on unpublished data, measures of visual search and movement inhibition were expected to exhibit a moderate to strong relationship with Driving Scores. A sample size of at least 68 subjects was needed to obtain a medium effect size ($f^2 \geq 0.15$) in a model with two predictors at a confidence level of 0.05 and a power level of 0.8.

Chapter 3 RESULTS

3.1 Participant Characteristics

Data were collected from 23 stroke survivors ranging in age from 48 to 84 (mean = 63, SD = 8.17). Participant's demographics and clinical information are summarized in Table 3.1. All subjects provided informed consent before participating in the study. This sample size provided a low power level of 0.32 to find medium effect size ($f^2 \leq 0.15$) in a model with two predictors at a confidence level of 0.05.

3.2 Individual Predictors of Driving Scores

Results of the bivariate regression are summarized in Table 3.2. Five measures were predictive of Driving Scores (medium effect size $f^2 \geq 0.15$) including measures related to visual search ($f^2 = 0.621$), motor inhibition (Distractors Avoided $f^2 = 0.366$), visuomotor performance (Total Fixations $f^2 = 0.621$), motor execution (Speed Peaks $f^2 = 0.297$), and task switching (Time difference $f^2 = 0.262$). The residuals from each bivariate regression were normally distributed (Kolmogorov-Smirnov tests, all $p > 0.05$), indicating that regression fits were not driven by outliers.

Measures	Subjects (n = 23)
Age	63yr [48, 84]
Sex	15 male, 8 female
Race	13 W, 10 AA
Handedness	19 right, 4 left
Stroke Side	22 right, 1 left

Table 3.1. Subject demographics and clinical information.

Predictor Measure	***ß***	***SE***	r^2	f^2	$p_{Regression}$	$P_{Normality}$
Total Fixations	-0.619	0.167	0.383	**0.621**	0.001	0.273
Distractors Avoided	0.518	0.182	0.268	**0.366**	0.010	0.243
Total Time	-0.554	0.177	0.307	**0.443**	0.005	0.139
Speed Peaks	-0.478	0.187	0.229	**0.297**	0.018	0.130
Time Difference	-0.456	0.190	0.208	**0.262**	0.025	0.540
Speed Bias	0.325	0.202	0.105	0.118	0.121	0.286
Divided Attn Speed	-0.195	0.209	0.038	0.039	0.362	0.251
Selective Attn Speed	-0.135	0.211	0.018	0.019	0.530	0.223
Objects Foveated	-0.084	0.212	0.007	0.007	0.698	0.161
Age	-0.061	0.213	0.004	0.004	0.778	0.135
Targets Hits	0.051	0.213	0.003	0.003	0.815	0.162

Table 3.2: Prediction of Driving Scores-Individual Predictors. A bivariate regression model revealed five predictors out of the eleven to have medium effect size of $f^2 \geq 0.15$. These predictors include Total Fixations, Distractors Avoided, Total Time, Speed Peaks, and Time Difference.

3.3 Independent Predictors of Driving Scores

Results of the multiple regression analysis are summarized Table 3.4. Three of the five individual predictors of Driving Scores, including Total Fixations, Total Time, and Speed Peaks, exhibited high intercorrelations (Table 3.3, $r \geq 0.707$). Of these three measures, the two weakest predictors of Driving Scores (Total Time, Speed Peaks) were excluded from the multiple and stepwise regression analyses to prevent multicollinearity. Multiple regression using Total Fixations, Distractors Avoided, and Time Difference as predictors of Driving Scores revealed a significant overall fit ($F^2 = 0.742$, $P < 0.01$) with normally distributed residuals (Kolmogorov-Smirnov test, $p = 0.340$). Further analyses of the individual predictor measures found that only Total Fixations was independently predictive of Driving Scores (medium effect size, $sf^2 = 0.344$).

Stepwise regression was subsequently used to test for overfitting of data in the multiple regression analysis. Results of the stepwise regression analysis are summarized in Table 3.5 and are illustrated in Figure 3.2. A simpler model that only included Total Fixations and Distractors Avoided as predictors of Driving Scores provided the best overall fit ($F^2 = 0.752$) and had normally distributed residuals (Kolmogorov-Smirnov test, $p = 0.396$). In addition, both predictor measures in this model were independently predictive of Driving Scores (Total Fixations: $sf^2 = 0.411$, Distractors Avoided: $sf^2 = 0.158$). Figure 3.2 confirms this finding by showing that removing Time Difference simplified the overall model while having a negligible impact on prediction of Driving Scores

Predictor Measure	Dist Avoided	Total Time	Total Fixation	Speed Peaks	Time Difference
Distractors Avoided	1				
Total Time	-0.426	1			
Total Fixations	-0.449	**0.949**	1		
Speed Peaks	-0.466	**0.874**	**0.812**	1	
Time Difference	-0.457	0.409	0.386	0.478	1

Table 3.3: Predictor Measure Correlations. This analysis controlled for multicollinearity. Predictors Total Time, Total Fixations, and Speed Peaks were found to have a shared variance. Due to Total Fixation's ($f^2 = 0.621$) from the bivariate regression (TF) moved to further analysis while Speed Peaks and Total Time were dropped.

	DF	*MSE*	$R^2_{Adjusted}$	F^2	$P_{Normality}$
Full Model	20	0.574	0.426	**0.742**	0.340
	ß	*SE*	sr^2	sf^2	$sp_{Predictor}$
Total Fixations	-0.444	0.186	0.197	**0.344**	0.027
Distractors Avoided	0.238	0.193	0.057	0.099	0.231
Time Difference	-0.175	0.186	0.031	0.054	0.358

Table 3.4: Prediction of Driving Scores-Multiple Regression. Ultimately due to its effect size Total Fixations was put with Distractors Avoided and Time Difference within the multiple regression model. This analysis shows both Total Fixations and Distractors avoided to be significant.

	DF	*MSE*	$R^2_{Adjusted}$	F^2	$P_{Normality}$
Full Model	21	0.571	0.429	**0.752**	0.396
	ß	*SE*	sr^2	sf^2	$sp_{Predictor}$
Total Fixations	-0.484	0.180	0.234	**0.411**	0.014
Distractors Avoided	0.300	0.180	0.09	**0.158**	0.111

Table 3.5: Prediction of Driving Scores-Stepwise Regression. Finally, a stepwise regression was performed and supported the model of Total Fixations and Distractors avoided as the two strongest independent predictors or post-stroke driving scores.

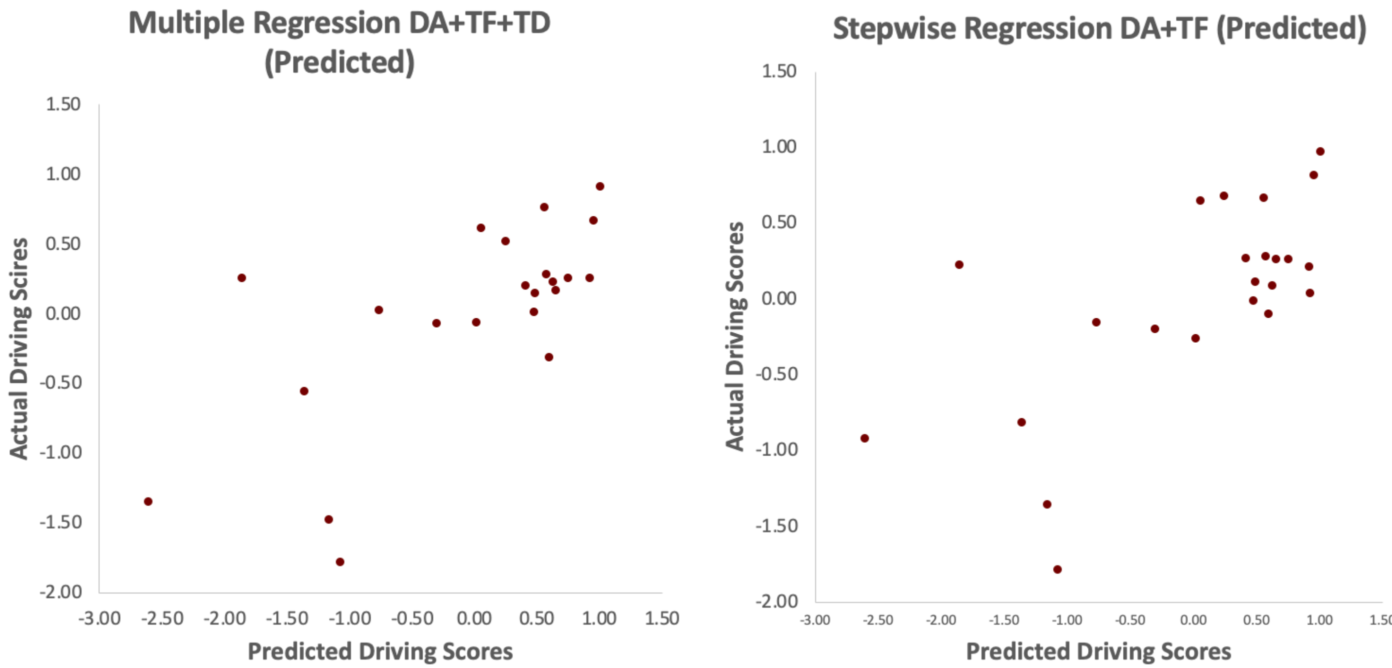

Figure 3.1: Predicted vs. Actual Driving Scores. These two graphs are comprised of the multiple and stepwise regression models depicting how each model's predicted driving scores correlates with participant's actual driving scores. The graph on the left is the regression model with Distractors Avoided (DA), Total Fixations (TF), and Time Difference (TD). The graph depicts a positive correlation between actual and predicted scores. The graph on the right is the final model where a stepwise regression analysis was performed with only (DA) and (TF). The removal of predictor (TD) slightly improves the model, overall, while maintaining a positive correlation between predicted and actual driving scores.

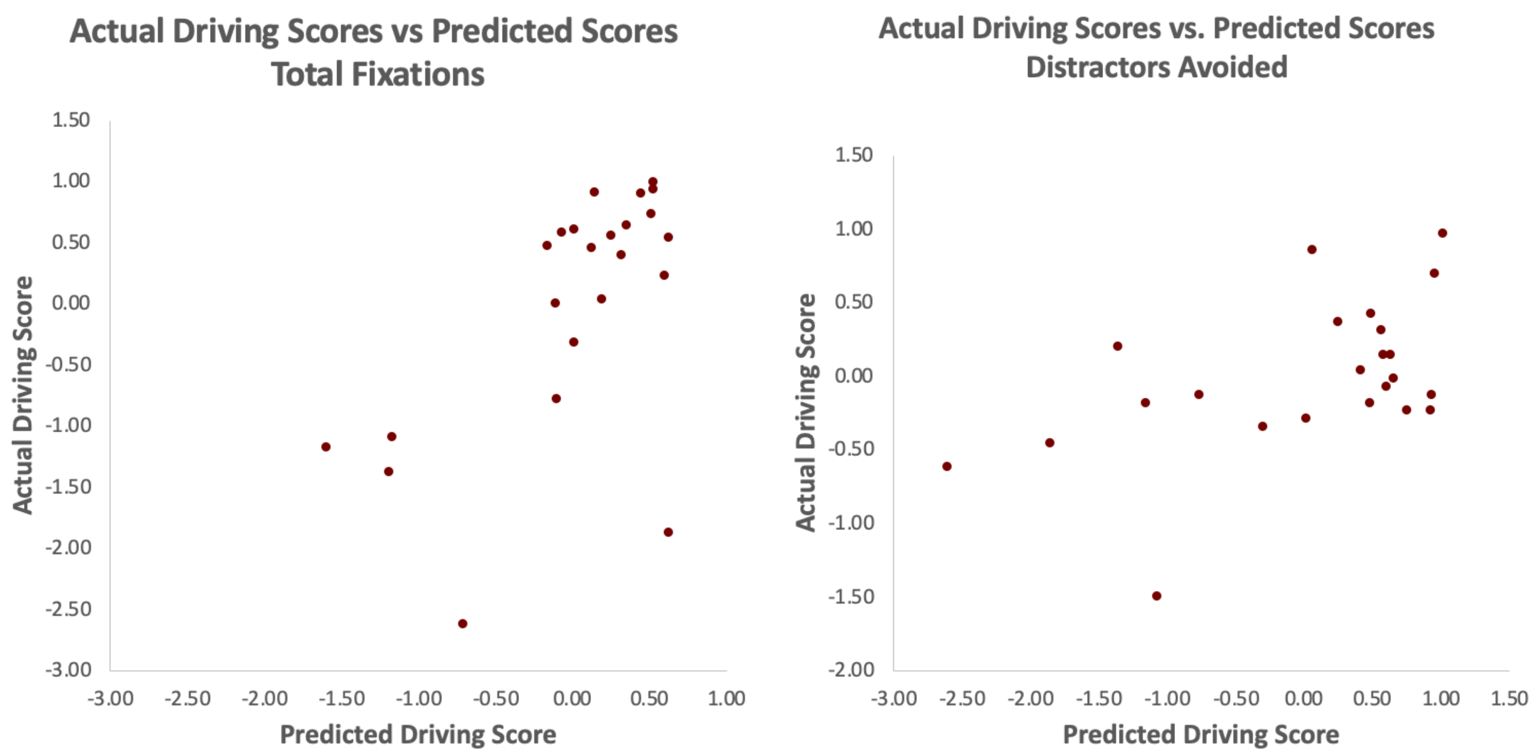

Figure 3.2: Predicted vs. Actual Driving Scores (TF vs. DA). Like Figure 6 the predicted and actual scores were comprised with a graph looking at Total Fixations (TF) and Distractors Avoided (DA) independently and their relationship with the participants driving scores. TF has a stronger positive correlation than DA suggesting TF to be a stronger predictor of actual scores than DA.

Chapter 4: DISCUSSION

4. Discussion

In support of our hypotheses, the present study demonstrated that measures of visual search (Aim 1) and motor inhibition (Aim 2) are predictive of driving proficiency after stroke independent of their relationships with other predictors. By identifying novel predictors of driving proficiency after stroke, this research may contribute to the future development of assessments and interventions that can improve our ability to predict and enhance on-road driving performance.

4.1 Visual Search Independently Predicts Driving Scores

The finding that Total Fixations in TMT-A was a strong predictor of Driving Scores highlights the importance of visual search as a strong predictor of post-stroke driving performance. Visual search plays a critical role in functional tasks by actively gathering information through eye movements and fixations. Accordingly, this result shows that assessments of visual acuity, peripheral vision, and visual processing speed may not provide sufficient prediction of driving proficiency because they fail to assess how efficiently visual information is gathered. In addition, the relationship between visual search and reaching control/motor execution further supports the significance of visual search in motor learning and performance (Singh et al, 2018).

4.2 Motor Inhibition Independently Predicts Driving Scores

The results of this study demonstrate that motor inhibition, as measured by Distractors Avoided, is a strong predictor of post stroke driving proficiency. While previous research has shown that impairments in executive functions can negatively affect driving, the specific role of inhibitory control of movement in post-stroke driving proficiency has not been extensively investigated. Many motor skills, including driving, require the ability to inhibit movements, thus interventions should explore ways to improve motor inhibition as a way of improving overall driving performance.

This result shows that assessments of motor impairment, like the Fugl-Meyer Assessment, may not be sufficient to understand deficits in the performance and learning of complex tasks such as driving. Specifically, deficits in motor execution and motor inhibition may persist in stroke survivors, leading to suboptimal performance in driving and other functional activities. Given that motor inhibition is rarely assessed post-stroke, clinicians should incorporate motor inhibition into assessments of visuomotor impairments.

4.3 The Unpredictive Nature of UFOV Measures for Driving Scores

The Useful Field of View (UFOV) test has been used as an informative measure of visual processing abilities during driving. However, recent systematic reviews suggest that the UFOV test, while valuable, may not provide a comprehensive assessment of visual input during driving. Results in the current study support the findings of these systematic reviews since measures for UFOV (Divided Attn. Speed and Selective Attn. Speed) were not found to be a strong independent predictor of driving scores (Table 4.1).

The rationale behind the limited power of the UFOV test in predicting driving scores can be attributed to the inherent nature of the task itself. The UFOV test primarily relies on an individual's capacity to identify and locate visual stimuli that are only present for a brief duration. Individuals then have an unlimited amount of time to indicate the identity and location of the target stimulus. The brief presentation of visual stimuli and unlimited time to respond are very different from real-life driving, thus indicating that UFOV lacks ecological validity.

This indicates a need for more applied research that directly involves driving to update our basic understanding of how drivers acquire information about their operating environment. In the context of stroke survivors, who often experience ongoing difficulties with functional activities despite passing neuropsychological test, it becomes crucial to identify other impairments that contribute to chronic challenges in performing continuous visuomotor tasks such as driving. Further investigations are needed to explore additional predictors of fitness to drive in this population.

4.4 Limitations

Though the results supported both aims, it is important to acknowledge three key limitations of this study. First, the cross-sectional design cannot provide strong evidence because it precludes the ability to establish causal relationships between the predictors identified in this study and driving performance. Experimental studies of appropriate interventions are needed to provide stronger evidence that visual search and motor inhibition directly contribute to droving proficiency.

Second, the study was limited to stroke survivors, thus the ability to generalize the findings to other populations, such as individuals with other neurological disorders,

requires caution. Future research needs to examine the generalizability of these findings to broader range of populations.

Third, the generalizability of these results to real-world driving performance is limited by the utilization of a driving simulator to assess driving performance and the use of a robotic device to assess visual search and motor inhibition. While these technologies provide valuable objective data, they may not fully capture the complexities and real-world challenges faced by stroke survivors when driving on actual roads. The ecological validity of the findings needs to be established by examining the extent to which the robotic measures of visual search and motor inhibition are predictive of driving performance in on -road settings.

4.5 Future Research

Overall, this study highlights the significance of visual search and motor inhibition as independent predictors of driving proficiency after stroke. These findings have important implications for the development of assessments that can better predict on-road driving performance and the design of interventions aimed at enhancing functional task performance, including driving, in stroke survivors. Further research is needed to deepen our understanding of the nature of the complex relationships between driving performance and impairments of visual search and inhibitory control.

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