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Driving Simulator Performance in Novice Drivers with Autism Spectrum Disorder: The Role of Executive Functions and Basic Motor Skills

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Abstract Previous studies have shown that individuals with autism spectrum disorder (ASD) demonstrate poorer driving performance than their peers and are less likely to obtain a driver's license. This study aims to examine the relationship between driving performance and executive functioning for novice drivers, with and without ASD, using a driving simulator. Forty-four males (ages 15–23), 17 with ASD and 27 healthy controls, completed paradigms assessing driving skills and executive functioning. ASD drivers demonstrated poorer driving performance overall and the addition of a working memory task resulted in a significant decrement in their performance relative to control drivers. Results suggest that working memory may be a key mechanism underlying difficulties demonstrated by ASD drivers and provides insight for future intervention programs.

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Introduction

The recent increase in research on motor vehicle driving for individuals with autism spectrum disorder (ASD) reflects an improved understanding of the disorder's lifetime course and changing functional impairments across development (Classen and Monahan 2013; Classen et al. 2013; Cox et al. 2012; Huang et al. 2012; Reimer et al. 2013; Sheppard et al. 2010). While many individuals with ASD have secured a driver's license and are able to safely operate a motor vehicle, emerging research indicates that the acquisition of safe driving skills is difficult for this population (Classen et al. 2013; Cox et al. 2012; Huang et al. 2012). Specifically, adolescents and young adults with ASD are less likely than their peers to acquire a driver's license (Cox et al. 2012), are more likely to become anxious during driving (Reimer et al. 2013), and are less likely to identify socially relevant road hazards (e.g., pedestrians; Sheppard et al. 2010) and monitor all relevant visual fields during driving (Reimer et al. 2013). In addition, simulated driving studies suggest that individuals with ASD demonstrate difficulties with specific driving skills including motor coordination, speed regulation, lane maintenance, signaling, and adjustment to unexpected events (Classen et al. 2013).

Collectively, experimental and survey studies are consistent in documenting motor vehicle driving as a critical area of functional impairment for adolescents and young adults with ASD. Only two studies (Classen et al. 2013; Reimer et al. 2013), however, have used driving simulators to assess driving skill in ASD, and neither of these studies have investigated the neurocognitive mechanisms and processes associated with these difficulties. Investigation of this relationship is warranted given the critical role that motor vehicle driving plays in adolescent development and functional independence for individuals with and without ASD. For example, acquiring a driver's license is associated with increased participation in full-time academic programs, plans to attend college, and a history of paid employment for adolescents with ASD relative to age-eligible but non-driving adolescents with ASD (Huang et al. 2012). As such, identifying factors associated with the development of safe driving skills is critical for developing driver training programs with the potential to improve functional outcomes and independence for adolescents and young adults with ASD.

Executive Functioning

Executive functions refer to a cluster of prefrontally mediated cognitive functions (e.g., working memory, response inhibition, set shifting) needed to perform goal-directed actions (Miyake et al. 2000; Rapport et al. 2013). Interestingly, the maturation of executive functioning in typically developing individuals parallels the decline in vehicular collisions; both plateau around age 25 (National Highway and Transportation Safety Administration 2008; Zelazo et al. 2004). Additionally, lower levels of executive functioning have been associated with higher frequency of vehicular collisions, and groups at high risk for vehicular collisions (e.g., individuals with ADHD or Depression; Vaa 2014; Bulmash et al. 2006) have been previously identified to have lower levels of executive functioning (Kasper et al. 2012; Snyder 2013; Willcutt et al. 2005).

Executive functioning deficits have been well documented in the ASD literature (Hill 2004; Liss et al. 2001; Ozonoff et al. 1991). In addition, several researchers have hypothesized that many ASD symptoms—including decreased theory of mind, anticipation of consequences, inhibition, planning, and problem solving—may be outcomes of these executive functioning deficits (Banich 2004; Hill 2004; Ozonoff et al. 1991). Given the robust association between executive dysfunction and impaired driving in other populations (Mäntylä et al. 2009; Lambert et al. 2014; Watson et al. 2013), it appears likely that such deficits may contribute to driving problems for individuals with ASD. However, little is known about the extent to which underdeveloped executive functions impact motor vehicle driving performance for adolescents and young adults with ASD, and critically, *which* executive functions affect driving performance for drivers with ASD (Classen and Monahan 2013). Understanding the mechanisms and processes underlying adverse driving outcomes from this population is critical to designing and assessing driving training programs and accommodations for this population.

Rationale, Significance, and Purpose

Driving is an important milestone for adolescents and young adults, and a critical step toward independence (Monahan 2012; Womack and Silverstein 2012). Although little is known about driving abilities of individuals with ASD, previous studies have identified this population to be less likely to obtain a driver's license and to demonstrate poorer driving performance than their same-aged peers (Classen et al. 2013; Cox et al. 2012). Virtual reality driving offers an ideal, safe environment to assess and provide targeted intervention to individuals who are in the process of obtaining their driver's license (Adler et al. 1995; Brooks et al. 2013; Hoffman et al. 2002).

The purpose of this study is to examine the association between driving performance, basic skills, and executive functioning among adolescents and young adults with and without ASD using a mid-level virtual reality driving simulator (VRDS). Novice drivers with ASD and healthy controls completed two driving simulation paradigms: (1) a *tactical* drive to assess overall driving performance within a simulated driving course; and (2) an *operational* drive that assessed basic skills (reaction times for steering, braking), and executive functioning (dual processing, response inhibition, working memory) within driving relevant scenarios. Following previous studies (Classen et al. 2013; Reimer et al. 2013; Sheppard et al. 2010), we hypothesized that drivers with ASD would perform worse than novice healthy control drivers during the tactical drive as well as during driving-relevant executive function tasks. We further hypothesized that executive dysfunction would significantly predict impaired driving performance for ASD relative to healthy control drivers and greater severity of ASD symptoms would be associated with worse driving performance. No predictions were made regarding the specific executive functions that would predict ASD driving difficulties given the paucity of literature for this population.

Methods

Participants and Simulator Design

Participants

Subjects were 44 male adolescents and young adults, 17 with ASD and 27 healthy controls. Subjects in the ASD group were between the ages of 15 and 23, had obtained their learner's permit, and had previously received a DSM-

IV (APA 2000) diagnosis of an ASD (Autistic Disorder, $n = 4$; Asperger Syndrome, $n = 7$; PDD-NOS, $n = 3$). The drivers with ASD were recruited as part of a driving training study; the healthy controls completed the same simulator tasks as the ASD group, and were recruited for another study of adolescents whom had recently obtained their driver's license. All ASD participants self-identified as White/Caucasian; of the comparison sample, two participants' ethnicity were Asian/Pacific Islander, one was Hispanic, one preferred not to respond, and the remaining were White/Caucasian (Table 1).

Criteria for inclusion were as follows: individuals between the ages of 15–25, with a diagnosis of an ASD (including but not limited to: Asperger's, Autistic Disorder, PDD, PDD-NOS), with their learner's permit at the time of pretest. Individuals must be able to comprehend how to and physically operate the driving simulator and experience no to minimal Simulation Adaptation Syndrome symptoms. The diagnosis of an ASD must be from a clinical psychologist or medical physician (i.e., not by school district). The source of diagnosis was based on parent report and the investigators did not independently obtain records to confirm source or classification of diagnosis. However, in order to be eligible for the study, participants must have met criteria for ASD (T-score > 60) on the parent report version of the Social Responsiveness Scale (SRS; Constantino and Gruber 2002) or the Social Responsiveness Scale-Second Edition (SRS-2; Constantino and Gruber 2012). As an updated version of this measure was released during the course of this study, the newer version of this widely used diagnostic measure was administered to parents of participants enrolled in the study after January, 2013 ($n = 8$). The BASC-2 parent form (Reynolds and Kamphaus 2004) was administered also to allow preliminary examination of the relation between parent-reported adaptive functioning (Adaptive Skills scale) and driving performance. Individuals with the following comorbid diagnoses/conditions were excluded from the study: brain injury, mental retardation(MR)/intellectual disability (ID), genetic or chromosomal disorder (e.g., Down Syndrome, Prader-Willi Syndrome, Fragile X, Angelman Syndrome), severe physical, medical or psychiatric condition that impairs driving ability (e.g., muscular dystrophy, psychosis). Additionally individuals requiring adaptive equipment to drive, such as hand accelerators or pedal extenders were excluded from the study. As mentioned above, ASD subjects were recruited for a larger driving training study; this manuscript is based on pre-intervention data only.

The university's Institutional Review Board approved both studies and all participants signed an informed consent form; participants under age 18 signed an assent form and a parent signed the consent form.

Simulator

We employed the commercially available Driver Guidance System (DGS-78), a mid-level driving simulator (Fig. 1). This simulator displays a 210° field of view on a curved screen inside an 8 foot cylinder. The simulator includes seatbelt, dashboard, steering wheel, turn signal, gas and brake controls, right, left, side, and rearview mirrors, as well as an adjustable seat. A unique capability of this simulation protocol is that it can allow for the evaluation of a battery of operational driving *abilities* and driving *skills* using two stages: operational tests and a tactical driving scenario.

The operational tests parallel basic neuropsychological tests, with the use of driving-relevant stimuli, requiring driving-relevant responses, in a driving context.

The tactical test involves driving 2.6 miles of rural, 4.3 miles of highway, and 2 miles of urban roads, negotiating routine driving events (e.g., stop lights, stop signs, speed limit changes) and unanticipated events that require defensive braking (e.g., parked car pulling into driver's lane; cross-traffic motorcyclist pulling into driver's path) and defensive steering (e.g., oncoming car swerving into driver's lane; rear approaching bicyclist while turning right). A total of 12 challenge events are included within this scenario at regular intervals throughout the tactical

Table 1 Group comparison of demographic characteristics

	ASD (n = 17)		Comparison (n = 27)		Analysis		
	Mean	SD	Mean	SD	t	p	x^2
Age (years)	18.28	2.29	16.59	0.55	3.69	<.001***	
	n		n				
Gender (male)	17		27				44.00
Ethnicity (Caucasian)	17		23				2.77

* $p < .05$; ** $p < .01$; *** $p < .001$

Fig. 1 Driver guidance system (DGS-78)

course (detailed in Table 2). The following four classes of driving variables are monitored and summed into a tactical composite score (detailed below): braking, speed control, steering, and judgment. All participants completed the operational tests prior to the tactical driving scenario; the duration of the tactical course varied depending on the driver's accuracy and efficiency in completing the course.

Previous investigations have demonstrated that simulators are a valid tool to assess a variety of driving performance measures such as lane position, speed, divided attention, and risky driving behaviors (Godley et al. 2002; Kaptein et al. 1996; Mullen et al. 2011). Simulators also appear sensitive to age-related changes in driving performance and cognition (Brouwer et al. 1991; Lambert et al. 2013; Strayer and Drew 2004). Previous investigations using prior versions of this simulation protocol with senior drivers have demonstrated that performance parallels on-road driving performance (Cox and Cox 1998) and the tactical composite score identified drivers at an elevated risk of future collisions (Cox et al. 1999). In regard to the simulation protocol utilized in the current investigation, reliability and validity data was collected at two Virginia Department of Motor Vehicle (DMV) sites on a large normative sample ($N = 448$) of experienced adult drivers, between the ages of 25 and 75 (mean age = 40) with an average of 27 years of driving experience. The tactical composite (overall driving performance score, detailed below) demonstrated a robust 2-week test–retest reliability of .86, discriminant validity for differentiating experienced from novice drivers ($p < .05$), and predictive of future driving performance ($R^2 = .73$, $p = .002$; Cox et al. 2015).

Driving Simulator Procedure

Operational Driving Tasks

Operational tasks consisted of four parts: motor tasks/contingency training and three executive functioning tasks assessing: dual processing, response inhibition, and working memory. Dependent variables (detailed below) for the operational tasks included: steering and braking response times (in seconds) during the motor tasks, and number of correct responses the three executive functioning tasks. A second dependent variable was collected as part of the working memory test, number of signs correctly recalled. The operational composite was calculated using the average z-score of these six individual variables. Sample z-scores are derived using scores from the study sample; DMV z-scores are calculated using scores obtained from the DMV normative sample.

Motor Tasks/Response Contingency Training

In this first scenario, each driver was required to process and employ two driving instruction goals presented in two separate training tasks to create response prepotency prior to the inhibition task. For both tasks, the driver followed a lead vehicle at a fixed speed, distance, and lane position. The first goal was braking; during this scenario, the lead vehicle's brake lights came on 10 times periodically for short (0.5 s; 5 occurrences) or long (3 s; 5 occurrences) durations. Drivers were instructed to remove their foot from the accelerator and press the brake as soon as both short and long brake lights were detected. Following the braking task, drivers engaged in a steering task. During this task, the lead vehicle's rear wheels passed over six "filled" potholes that were gray and six "unfilled" potholes that were black, three of each from beneath the left wheel and three of each from beneath the right wheel. Drivers were instructed to avoid both filled and unfilled potholes by steering around the potholes without leaving their lane. The primary purpose of these two tasks was to create prepotent responses to the dependent variables that were assessed later in the response inhibition and working memory tasks. Additionally, reaction times for all steering (hand/arm coordination) and braking (foot/leg coordination) trials were recorded. Braking (foot/leg) reaction time was the elapsed time in milliseconds between brake lights coming on and the participants' applying 5 lbs. of pressure to the brake pedal. Steering (hand/arm) reaction time was the elapsed time in milliseconds between when the pothole appeared and the initiation of a steering maneuver. Drivers

Table 2 Driving challenges in tactical virtual drive

1. Posted speed limit changes
   1.1. 3 Increases
   1.2. 5 Decreases
2. Turns
   2.1. 4 Left turns
   2.2 3 Right turns
      2.2.1. 2 Right exits/entrances
3. Road type
   3.1. 2 miles of Urban
   3.2. 2.6 miles Rural
   3.3. 4.3 miles of Highway
4. Challenge events
   4.1. As driver approaches a 2-way stop intersection where they have right-of-way, a motorcycle crosses right to left, requiring them to brake to avoid a collision.
   4.2. Driver is asked to turn left at the next intersection, while a motorcycle is approaching in the on-coming lane. Driver must allow them to pass before proceeding.
   4.3. Driver is on a two-lane road with a police car approaching from the rear with their siren on. They must pull over to the right and allow them to pass.
   4.4. Driver is asked to turn right at a stop-signed intersection. Traffic is approaching from the left, and they must choose reasonable gap to make the turn.
   4.5. Driver is asked to turn left at 6th, but they first pass 5th street. They need to recognize the appropriate street. Also, while approaching 5th street a car is seen approaching quickly from the right and makes a wide right turn without stopping in an effort to distract the driver.
   4.6. As driver travels down a 2-way road, a parked car pulls out from the right directly in front of them, requiring driver to quickly stop to avoid a collision.
   4.7. Driver is making a right turn from a stop-signed intersection. Cars are approaching first from the left, then from the right, and then once more from the left but with gaps allowing the driver to turn.
   4.8. Driver is on a 2-way road. Immediately after cresting a hill, an on-coming car drifts into the driver's lane, requiring them to move over to the right.
   4.9. As driver approaches a red light they pass a cyclist. When the driver stops at the light, the cyclist catches up and stops at a point visible in their right side mirror. The driver has to wait until the light is green to turn, and when they start rolling forward the cyclist accelerates. The driver needs to slow and allow them to pass before making the turn.
   4.10. While on a 65 mph highway, three cars pass in the adjacent lane going 80 mph. Driver needs to avoid urge to speed in order to 'go with the flow of traffic'.
   4.11. Still on the highway, driver is asked to pass a 55 mph lead car while cars are approaching from the rear in the adjacent lane. Driver needs to use left mirror to choose an appropriate time to change lanes and pass.
   4.12. While in the center lane, driver is asked to exit the highway. The right lane has cars in it, so they need to use their right mirror to choose an appropriate time to change lanes and exit.

completed ten trials of braking followed by twelve trials of steering, presented at jittered intervals (i.e., varied duration between trials).

Executive Function Test 1: Dual Processing Task

In this scenario, the braking and steering tasks were combined, such that drivers were required to attend and respond concurrently to brake lights *and* potholes. Drivers completed a total of 16 braking and steering trials (8 of each), presented in a standardized order at jittered intervals during this second operational test. The dual processing task served to further establish response prepotency in preparation for the inhibition task described below. The dependent variable of interest in this task was total percentage of correct responses, which includes percentage correct brake responses (braking in response to short and long brake lights) and percentage correct steering responses (steering in response to filled and unfilled potholes).

Executive Function Test 2: Response Inhibition Test

Response inhibition refers to the ability to suppress the processing, activation, or expression of information (or action) that would otherwise interfere with the attainment of a desired cognitive or behavioral goal (Dagenbach and Carr 1994; Dempster 1992). This third operational test required drivers to inhibit 2 of the 4 previously trained prepotent responses. This time, they were instructed *not* to press the brake when the brake lights came on for a short duration and only press the brake in response to long brake lights. Similarly, participants were instructed to ignore filled potholes by refraining from steering around them, but to continue to steer around unfilled potholes. In this scenario, all drivers completed 16 braking and steering trials (8 trials of each), presented in standardized order at jittered intervals.

The dependent variable of interest was the percentage of total correct responses, comprised of correct braking responses (braking in response to long brake lights, not braking to short brake lights) and correct steering responses (steering in response to unfilled potholes, not steering in response to filled potholes).

Executive Function Test 3: Working Memory Test

Working memory is a limited capacity system responsible for the temporary storage, rehearsal, updating, and mental manipulation of information for use in guiding behavior. Working memory has been linked to a number of real world skills including driving (Cohen and Conway 2007). The working memory operational test was modeled after the automated operation span task (Conway et al. 2005; Unsworth et al. 2005) to provide an index of overall working memory functioning. Thus, it is a complex span task that requires participants to hold an increasing quantity of information (road signs) while simultaneously performing an attention-demanding secondary processing task (inhibit/not inhibit steering/braking) that places demands on the same stimulus modality (visual). This test was built upon the previous tests by requiring the participant to remember presented road signs while adhering to the response inhibition instructions from the previous scenario. Drivers were given the same instructions as the response inhibition scenario. In addition, they were told they would be passing common road signs and were instructed to remember these signs in the order presented for a later test. There were 18 unique nonverbal standard road signs (e.g., Airport, Hospital, Library) presented randomly. After passing a series of signs (ranging in number from 1 to 3), the driving simulator would automatically pause, and the driver would be presented with an array of the 18 signs on the simulator screen. The driver would then be asked to identify the signs, in the same serial order, they had passed since the last series. The working memory scenario consisted of 26 braking and steering trials, presented at jittered intervals. A total of 9 series of 1–3 road signs per series were presented at jittered intervals. The dependent variables of interest were percentage of total correct responses during the driving task (the same as described for the response inhibition test upon which the working memory test is built), and the number of road signs recalled in the correct serial order (out of 18 possible).

Tactical Driving Test

The tactical driving test monitored 31 performance variables, such as swerving, rolling stops, speeding, and collisions. Fourteen of these 31 variables were selected a priori based on evidence from data collected from the DMV VRDS normative sample (448 adults, ages: 25–70; Cox et al. 2015) that they significantly predict on-road accident rates. These 14 variables are grouped conceptually into four primary skill areas: braking, speed control, steering, and judgment. Braking variables include: Rolling Stops [ratio of incomplete (>0 and <5 mph) to complete (0 mph) stops], Deceleration Smoothness (total magnitude of rapid decelerations; i.e., slamming on brakes), Collisions (number of collisions with another vehicle >5 mph), and Bumps (number of collisions $\leq$5 mph). Speed control variables include: Acceleration Smoothness (total time when accelerator position is rapidly changing; i.e., slamming on gas; >0.2 units of pedal position range 0–1), Speed Plus 5 MPH (total time spent driving 5–19 mph above the posted speed limit), Speed Plus 20 MPH (total time spent driving 20+ mph over the posted speed limit), and Tailgating (number of times driver is within 15 feet of lead car in open road condition). Steering variables include: Lane Position Variability (standard deviation of lane position while in "open road" condition; i.e., swerving); Midline (average magnitude active; composite score of how far across and for how long driver was in oncoming lane of traffic), Off Road (standard deviation time active; variability of time driver drove off road), and Off Road Resets (number of times driver failed to make a turn when instructed, requiring a reset to designated route). Judgment variables identified were: No Signal for Lane Change (number of lane changes without using turn signal) and Speed Minus 20 MPH (average time spent 20 mph or more under the posted speed limit). An overall Tactical Driving Composite was computed from these variables and served as the primary indicator of driving performance. This composite was calculated as an average of the z-scores across the 14 variables. Mean z-scores reflect standard deviations from the normative sample mean; positive and negative values indicate better and worse performance relative to the normative sample of experienced drivers, respectively. Z-scores for each variable were computed twice: once based on the current sample for the study's primary analyses, and separately relative to the normative DMV sample to provide additional insights into the driving performance of both groups relative to experienced drivers (presented in Tables 3, 4).

Data Analysis

We used a multi-tier approach to examine the interrelation among driving performance and executive functioning in adolescents and young adults with and without ASD. In the first tier, demographics and basic motor skills were assessed, and significant between-group differences were tested as covariates for all additional analyses. In the second analytic tier, we assessed between-group differences in tactical driving performance using the empirically derived Tactical Driving Composite, with Bonferroni-corrected post hoc tests to examine the extent to which any observed differences were attributable to specific driving behaviors. The third tier examined performance on the executive functioning tasks (response inhibition, working memory), and the final tier used ANCOVA to examine the extent to which ASD tactical driving impairments may be attributable to motor and executive functioning differences detected in the preceding tiers. A final set of exploratory analyses based on the ASD sample ($n = 16$) were used to facilitate hypothesis generation for future studies; parent symptom ratings were not available for the healthy control group. In this tier, Bonferroni-corrected correlations between parent-reported clinical variables (SRS-2 Total

Score, BASC-2 Adaptive Skills scale) and the Tactical driving variables were computed to explore the relations between driving behavior and clinical symptoms.

Due to simulator recording error, one ASD participant's tactical driving data were missing ($n = 43$). Similarly, five individuals (four ASD, one comparison) had non-usable operational task data due to using two feet (i.e., braking with left foot while simultaneously pressing gas with right foot) (final $n = 39$).

Results

Tier I: Demographics and Basic Motor Skills

There were no significant differences in race/ethnicity between the ASD and comparison group participants (Table 1), and all participants were male. However, the ASD group ($M = 18.29$, SD = 2.29) was significantly older than the comparison group ($M = 16.59$, SD = 0.55; $p < .01$). With regard to basic response speed (Table 3), the ASD group was significantly slower than the comparison group during the steering (hand/arm) motor task ($p < .001$) but not the braking (foot/leg) motor task ($p = .14$). Similarly, the groups did not differ significantly in performance on the combined steering/braking dual processing task ($p = .25$). Age and arm/hand reaction time were not significant covariates of any of the analyses reported below (all $p \geq .37$). We therefore report simple model results with no covariates.

Tier II: Tactical Driving Performance

As shown in Table 4, the comparison group performed significantly better on the Tactical Driving Composite than the ASD group ($p = .009$, $d = 0.88$). Exploratory post hoc analyses of the 14 variables that comprise the Tactical Driving Composite, corrected for multiple comparisons (critical $\alpha = .003$), revealed that these between-group differences were primarily attributable to "bumping" the lead car ($d = 1.09$), increased swerving (SD of lane position; $d = 0.26$), and increased lane changes ($d = 1.04$) (all $p < .003$).

Tier III: Executive Functioning

The 2 (group) × 2 (response inhibition, working memory) ANOVA for the percentage of correct steering and braking was non-significant for group ($p = .861$) and condition ($p = .831$), whereas the interaction effect was significant ($p = .006$) (Table 3). Post-hoc tests revealed that the significant interaction shown in Fig. 2 was attributable to the differential effects of adding working memory demands for ASD relative to non-ASD adolescents and young adults.

Table 3 Group comparison of operational driving performance on motor response, dual processing, response inhibition, and working memory tasks

Operational variable	ASD		Comparison		F	*p*	*d*
	n = 13		n = 26				
	M	SD	*M*	SD			
Composite							
Sample z-score	−0.24	0.51	0.09	0.32	5.40	.026*	0.41
DMV z-score	0.08	0.42	0.21	0.26	1.46	.235	0.93
Individual variables							
Braking reaction time (s)	1.21	0.26	1.1	0.2	2.34	.142	0.51
Steering reaction time (s)	0.93	0.15	0.75	0.11	17.32	<.001***	1.29
DP: No. of correct responses	14.85	2.23	14.04	1.91	1.39	.246	−0.41
RI: No. of correct responses	15.62	0.65	15	1.41	2.21	.146	−0.52
WM: No. of correct responses	24.54	2.5	25.35	1.16	1.92	.174	0.71
WM: No. of signs recalled	14.62	4.66	17.04	1.89	5.38	.026*	0.81

Operational composite calculated using the average z-score of the six included individual variables. Sample z-scores are derived using scores from the study sample; DMV z-scores are calculated using scores obtained from a DMV normative sample. Reaction times are reported in seconds. No. of correct responses = Number of correct steering and braking responses according to task instructions. For dual processing, correct responses reflect braking to long and short brake lights and steering around filled and unfilled potholes. For the inhibition and working memory tasks, correct responses reflect braking to long brake lights, not braking to short brake lights, steering around unfilled potholes, and not steering around filled potholes. Also for working memory task, no. of signs recalled = the number correct signs recalled in the correct serial order (out of 18); *ASD* autism spectrum disorder, *DP* dual processing task, *RI* response inhibition task, *WM* working memory task

* $p < .05$; ** $p < .01$; *** $p < .001$

Table 4 Group comparison of tactical driving performance

Tactical Variable	ASD n = 16 M	ASD n = 16 SD	Comparison n = 27 M	Comparison n = 27 SD	F(1,41)	*p*	*d*
Composite							
Sample z-score	−0.22	0.57	0.13	0.29	7.46	.009***	0.88
DMV z-score	−1.88	2.27	−0.33	0.85	10.24	.003***	1.03
Individual variables							
Acceleration, tot MA	56.62	36.1	28.92	24.96	9.11	.004**	0.98
Bumps	2.06	2.49	0.37	0.63	11.43	.002***	1.09
Collisions	2.19	3.39	0.41	1.01	6.56	.014*	0.83
Deceleration, tot MA	7.18	8.5	2.96	4.82	4.346	.043*	0.67
Lane Pos, SD Active	0.40	0.09	0.32	0.41	18.43	<.001***	0.26
Midline, avg MA	1.85	1.58	1.24	1.61	1.47	.232	0.39
No Signal #LnChange	22.19	13.7	12.85	4.91	10.44	.002***	1.04
Off road resets	0.38	0.81	0.04	0.19	4.39	.042*	0.68
Off road, SD TA	2.83	3.11	0.75	2.91	4.87	.033*	0.71
Rolling stop ratio	0.16	0.06	0	0	1.72	.197	4.51
Speed − 20 avg TA	5.75	2.9	5.33	6.88	0.05	.819	0.07
Speed + 20, tot TA	10.29	20.58	6.23	19.11	0.43	.516	0.21
Speed + 5, tot TA	62.57	79.62	78.36	84.24	0.37	.548	−0.20
Tailgating	3.44	2.13	2.22	2.03	3.48	.069	0.60

Tactical composite scores calculated using the average z-score of the 14 included individual variables. Sample z-scores are derived using scores from the study sample; DMV z-scores are calculated using scores obtained from a DMV normative sample. *Avg* average, *MA* magnitude active, *TA* time active, *Tot* total. Acceleration Total Magnitude Active = slamming on gas; Bumps = the number of collisions with another vehicle ≤5 mph; Collisions = the number of collisions with another vehicle>5 mph; Deceleration, Total Magnitude Active = slamming on brakes; Lane Position, Standard Deviation Active = swerving; Midline, Average Magnitude Active = how far across and how long driver is in lane of oncoming traffic; No Signal, Number Lane Changes = the number of lane changes made without using turn signal; Off Road Resets = number of times driver failed to make a turn when instructed; Off Road Standard Deviation Time Active = variability of time driver was off road; Rolling Stop Ratio = the ratio of rolling stops (>0 and <5 mph) to complete (0 mph) stops; Speed -20 Average Time Active = average time spent 20 mph or more under posted speed limit; Speed +20 Total Time Active = total time spent driving 20 mph or more over the posted speed limit; Speed +5 Total Time Active = total time spent driving 5–19 mph over the posted speed limit; Tailgating = number of times driver is within 15 feet of lead vehicle

* $p < .05$; ** $p < .01$; *** $p < .05/14$ (.003; alpha adjusted for multiple comparison)

That is, between-group differences in steering/braking did not reach significance for either the response inhibition ($p = .146$) or working memory ($p = .174$) conditions. However, the increase in working memory demands was associated with a significant one-tailed decrease in steering/braking performance for the ASD group ($p = .10$, $d = -0.45$) relative to a significant increase in steering/braking performance for the comparison group ($p = .016$, $d = 0.54$).

Examination of recall performance during the working memory complex span condition was consistent with the steering/braking performance changes reported above, and revealed that the comparison group recalled significantly more signs in the correct serial order than the ASD group ($p = .026$, $d = 0.81$) (Fig. 2; Table 3). Collectively, results of the executive functioning tests revealed that adding working memory demands to a complex driving task significantly disrupts driving performance for adolescents and young adults with ASD, as evidenced by significant increases in steering/braking errors and overall lower working memory performance.

Tier IV: The Association Between Working Memory, Motor Speed, and Tactical Driving

In the preceding analyses, we found that adolescents and young adults with ASD have significantly slower hand/arm reaction time (steering) and decreased working memory capacity relative to healthy controls. In the final set of analyses, we assessed the extent to which these difficulties

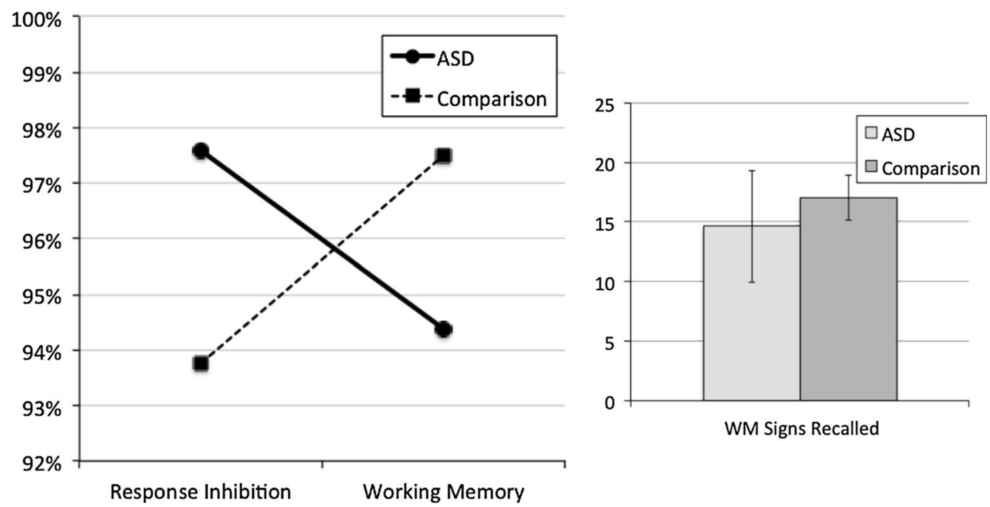

Fig. 2 Group comparison of performance on executive functioning tasks. *Note* Performance on response inhibition and working memory tasks measured by percentage of braking and steering errors; additionally, working memory is measured by number of signs recalled

were associated with their overall impaired tactical driving performance. To accomplish this goal, we repeated the Tier II analysis using ANCOVA to assess between-group differences in tactical driving performance with working memory (percent of signs recalled in the correct serial order) and hand/arm reaction time (s) as covariates. Results revealed that working memory ($p = .009$), but not hand/arm RT ($p = .73$) was a significant covariate of the Tactical Driving Composite; however, between-group differences in tactical driving performance remained significant ($p = .048$) after accounting for working memory. In other words, these results suggest that underdeveloped working memory abilities may help explain some of the tactical driving difficulties experienced by drivers with ASD, but additional variables will be needed to fully understand the mechanisms and processes underlying impaired driving performance among adolescents and young adults with ASD.

Tier V: Exploratory Association Between Clinical Rating Scales and Driving

In the final Tier, we examined the association between clinical rating scales (SRS-2 Total Score, BASC-2 Adaptive Skills Scale) and driving performance during the tactical and operational driving tasks for drivers with ASD ($n = 16$; clinical data was not available for the healthy control drivers). Across the tactical variables, clinical ratings correlated only with steering variables: driving across midline was correlated with BASC-2 Adaptive Skills ($r = -.57$, $p > .05$) and SRS-2 Total ($r = .76$, $p > .01$), and inconsistent lane positioning (SD of lane position, or 'swerving') was correlated with SRS-2 Total ($r = .70$, $p > .05$). Similarly, steering and braking reaction times correlated with BASC-2 Adaptive Skills ($r = -.54$ and $-.64$, respectively, both $p \leq .05$), and SRS-2 Total ($r = .55$ and .68, respectively, both $p \leq .05$). These findings are generally consistent with the between-group findings of difficulties in specific driving skills for adolescents and young adults with ASD, and suggest that future investigations may benefit from an individual differences approach to further identify clinical and cognitive predictors of driving difficulties for this population. These results should be considered preliminary and interpreted with caution, however, given the small sample size.

Discussion

The present study was the first to examine the impact of motor and executive functioning on tactical driving performance for adolescent and young adult drivers with ASD relative to healthy controls. Drivers with ($n = 17$) and without ($n = 27$) ASD completed a series of tactical and operational tasks in a mid-level driving simulator currently being tested by the Virginia DMV. Results revealed that drivers with ASD had significantly slower reaction times during steering ($d = 1.45$) but not braking. In addition, adolescents and young adults with ASD demonstrated impaired working memory functioning ($d = 0.81$), such that adding working memory demands resulted in a significant decrement in their driving performance relative to healthy control drivers. Importantly, working memory abilities, but not motor speed, served as a significant covariate of driving ability, suggesting that working memory may reflect an important mechanism underlying some of these drivers' on-road difficulties. In contrast, adolescent drivers with ASD performed similarly on driving tests assessing their ability to flexibly shift between steering and braking, and drivers with ASD successfully inhibited responses at similarly high levels relative to healthy control adolescents.

Results from the tactical drive reveal that adolescents and young adults with ASD demonstrated poorer overall driving ability within a simulated driving environment relative to novice drivers without ASD, despite being significantly older. This finding is consistent with previous investigations (Classen et al. 2013; Cox et al. 2012; Huang et al. 2012, Reimer et al. 2013), and extends this line of research by providing an initial examination of the role of executive dysfunction in these driving difficulties. Further, the current findings suggest the need for driving interventions and technological accommodations for this population given the association between tactical driving performance and on-road collisions (Cox et al., 1999, 2015). In the current study, the impaired driving simulation performance of drivers with ASD appeared attributable primarily to steering and braking performance, rather than speed control or judgment variables. Specifically, adolescent drivers with ASD were more likely to "bump" the car in front of them, and less likely to maintain consistent lane positioning relative to novice, non-ASD drivers. Given this pattern, we might expect an association between driving performance and basic motor skills associated with steering and braking. Basic hand-eye (steering) and foot-eye (braking) reaction time, however, were not significant covariates of tactical driving performance, suggesting that alternative mechanisms and processes are needed to explain driving difficulties for adolescents and young adults with ASD. Further, when engaged in a high stress simulated drive, including a number of driving-related challenges, the ASD group demonstrated errors that would be considered excessively rare to occur in an on-road evaluation, such as simultaneously pressing the brake and accelerator and increased lane changes. We believe this may be due to these participants' desire to press the brake as soon as possible, thus "cheating" by keeping their left foot over the brake while accelerating. These errors are picked up in data analysis; however, this does not trigger an alert during the drive, which would allow the operator to correct the driver and limit future errors. This also indicates that in these cases the simulator operator was not able to see the participants' feet during the drive, which should be modified in future protocols.

Deficits in executive functioning have been well-documented in the ASD literature (Hill 2004; Liss et al. 2001; Ozonoff et al. 1991); this study's findings highlight the influential role these higher order abilities play in driving performance for this population. Interestingly, the ASD group did not demonstrate impaired performance during response inhibition or dual processing tasks, whereas the addition of a working memory task (road sign recall) differentially impacted drivers with ASD. Not only did the ASD group recall significantly fewer signs in the correct serial order than the comparison group, but they also demonstrated a differential decline in their driving performance with these added cognitive demands. These results are consistent with previous findings that adolescents and young adults with ASD have particular difficulty with multi-tasking while driving (Cox et al. 2012; Reimer et al. 2013), and extend this literature by suggesting that working memory abilities significantly predict simulated driving performance, which has been found to parallel on-road driving performance in earlier investigations across other populations including brain-injured, young adult, and senior drivers (Cox et al. 1999; Lee et al. 2003; Lew et al. 2005; Shechtman et al. 2009; Underwood et al. 2011).

Recognizing that adolescents and young adults with ASD performed similarly to their peers on most aspects of simulated driving (braking speed, flexibly shifting between steering and braking, correctly inhibiting braking and steering based on road demands), the current results suggest that driver training interventions should focus specifically on those areas where this population demonstrates deficits. In other words, driving training for adolescents and young adults with ASD may exert maximum benefits by focusing on training scenarios that require increased working memory demands (e.g., multitasking)—particularly in the context of scenarios emphasizing consistent lane positioning and distance from a lead car—instead of more basic driving skills. Thus, we hypothesize that targeting working memory skills within a driving context (simulator) may improve driving-relevant working memory performance and expertise by increasing exposure to real-world scenarios that require this skill. Simulator-based interventions could also provide drivers with ASD a safe environment in which they would be exposed to multiple, relevant cognitive demands (e.g., sound system manipulation, GPS directions) while navigating a simulated course. Alternatively, assistive technology and adaptations could be developed to lessen the working memory demands required to operate a motor vehicle. Additionally, although difficult to enforce, guidelines for parents and instructors could also emphasize the minimization of potentially distracting stimuli/technology for this population. More general working memory training programs may hold promise as well; however, we caution against using commercially available, computerized "working memory" training programs at this time given converging meta-analytic and experimental evidence that these programs fail to improve working memory (Rapport et al. 2013; Shipstead et al. 2012).

Regarding future directions, the healthy control group's improved performance on the steering/braking inhibition task in response to increasing working memory demands was contrary to performance patterns of experienced drivers in the normative sample (Cox et al. 2015) and aging drivers (Lambert et al. 2013; Watson et al. 2013), and suggests some modification to the simulator protocol. Specifically, typically developing adolescents and young adults may require more demanding tasks within this context (e.g., higher working memory set sizes). This hypothesis is consistent with developmental research demonstrating that executive functions such as working memory peak in early adulthood before showing age-related decline (Park 2002), and when considered in the context of the present findings allow us to speculate that better developed working memory may provide a partial buffer against these driver's on-road inexperience.

Limitations

The unique contribution of the current driving simulation study was its investigation of the role of basic skills and executive functions in the driving difficulties experienced by adolescents and young adults with ASD. Several caveats require consideration when interpreting the present results. First and foremost, driver's skills were evaluated within a driving simulator, with protocols designed to test driving skills within a challenging simulation. Previous investigations have found performance within the simulation environment to be predictive on on-road performance (Godley et al. 2002; Lee et al. 2003; Lew et al. 2005; Shechtman et al. 2009; Underwood et al. 2011) but these results should not be considered equivalent to "real-world" driving. As mentioned above, pressing the accelerator and brake during braking tasks, unplanned lane changes, and collisions are expected to be rare events for on-road driving but occurred in higher rates within this protocol that regularly presented participants with difficult scenarios and unanticipated events. This investigation has also revealed the need for additional measures to better define our groups and provide additional insight regarding group differences. Specifically, a cognitive measure such as the WAIS could help to determine if cognitive differences contributed to group differences. For the ASD group, ASD classification and confirmation of symptoms were based on parent report; a confirmation of an ASD diagnosis by an independent clinician or physician would contribute another evaluation of current presentation could provide more detailed data regarding the clinical phenotype. Independent experimental replications with larger samples that include females, older drivers with ASD, and a more carefully matched comparison group are needed to confirm the present results. Notably, the comparison group was significantly younger but had recently obtained their license, whereas the ASD group had learner's permits. We acknowledge the limitation of not having a formal measure of driving experience for participants; parent-report of number of hours spent on the road proved unreliable and inconsistent across groups, as they were enrolled in two separate studies. In future investigations we plan to include a more detailed driving history questionnaire to help quantify previous driving experience. Although permit/license status and chronological age do not fully capture an individual's driving experience, the healthy control group likely had somewhat more driving experience, which may have contributed to the magnitude of observed group differences on the driving variables. In contrast, the increased age of the ASD group did not portend improved executive functioning as expected developmentally (Zelazo et al. 2004), and age was not a significant covariate in any of the analyses. Finally, working memory abilities predicted but did not fully account for between-group differences in driving performance, suggesting that future studies would benefit from examination of additional mechanisms and processes such as driver anxiety, specific ASD symptoms, social relevance of road hazards, and visual field monitoring (Reimer et al. 2013; Sheppard et al. 2010).

Clinical and Research Implications

The current study was consistent with previous research documenting motor vehicle driving difficulties in individuals with ASD (Classen et al. 2013; Cox et al. 2012; Huang et al. 2012; Reimer et al. 2013), and extends this line of research by identifying specific areas of difficulty within simulated driving paradigms (maintaining consistent lane position and distance from a lead car) and implicating a specific executive function—working memory—in the driving difficulties experienced by these adolescents and young adults. In contrast, novice drivers with ASD did not demonstrate impairments in most basic driving skills, and were able to successfully flexibly shift between braking and steering, quickly brake in response to a lead car's brake lights, and quickly process on-road demands to successfully inhibit braking and steering when necessary in a simulated driving environment. Clinically, these findings suggest that driver training programs for adolescents and young adults with ASD may provide maximum benefit through repeated practice of scenarios that place relatively high demands on working memory (e.g., multitasking) while emphasizing consistent lane positioning and distance from a lead car—instead of more basic driving skills. In addition to increasing expertise, we hypothesize that simulated driver training may further improve driving performance for adolescents and young adults with ASD by decreasing anxiety (Reimer et al. 2013) through physiological habituation processes to the extent that each training session is of sufficient duration (i.e., 90 min or more). Thus, we propose that simulator-based driver training studies use extended training sessions and measure driving skill and physiological arousal, both within and across sessions, to allow examination of the specific mechanisms and processes underlying training-related improvements for this population.

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Author Contributions SMC participated in the design and coordination of the study, performed the clinical measures and collected data for the ASD group, participated in developing the dataset, performing statistical analysis, interpretation of the data, and drafted the manuscript; DC conceived of the study, participated in the design and interpretation of the data, and helped to draft the manuscript; MK participated in the design of the study, participated in statistical methods and interpretation of the data, and helped to draft the manuscript; MM participated in developing dataset, performing statistical analysis and interpretation of the data; AL participated in the design and coordination of the parallel study for healthy controls (HC), also administered clinical measures and participated in design and interpretation of HC data that was utilized for this manuscript; RJ participated in the coordination of both the ASD and HC studies and administered the driving simulator protocol to participants from both groups; SAC participated in the coordination of the ASD study and administered clinical measures for ASD participants; RR participated in the design and coordination of the study and helped to draft the manuscript. All authors read and approved the final manuscript.

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