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ORIGINAL ARTICLE

Utility of a novel simulator paradigm in the assessment of driving ability in individuals with and without attention-deficit hyperactivity disorder

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Abstract

This study aimed to evaluate the utility of a novel, more cost-effective driving simulator, Assetto Corsa (AC), in detecting differences in driving performance between individuals with and without ADHD. Driving simulators are a useful means of assessing driving performance in those with attention-deficit hyperactivity disorder (ADHD); however, they are frequently expensive and thus unavailable to many researchers. A total of 87 participants (16 with ADHD, 71 without) completed an AC driving simulator task. They also completed computerized measures of attention and executive functioning and a questionnaire assessing self-reported driving behaviors and anger, ADHD and related symptoms, and mind wandering. Relative to those without ADHD, participants with ADHD reached higher average ground speeds and more greatly utilized the throttle. They also applied higher maximum pressure to the throttle and brake pedals. Within the full sample, greater mind wandering was associated with average and maximum throttle pressure and maximum ground speed. Findings confirm prior works indicative of a deleterious effect of ADHD diagnosis on simulator performance and may be attributed to a combination of impulsivity and mind wandering.

Keywords Simulation and virtual reality · Mental disabilities · Distraction · Driver behavior · Attentional processes

Introduction

Driving is the most popular method of transportation in the USA; the average American puts in over 13,000 miles behind the wheel each year (US Department of Transportation). However, driving is also potentially dangerous both to the driver and to the others on the road. In 2017, over 37,000 motor vehicle-related deaths occurred in the USA alone (National Highway Traffic Safety Administration 2018). Although other variables such as vehicle malfunction and environmental conditions are associated with collisions, human factors are considered to be the strongest contributor to motor vehicle collisions (Castro 2008).

Symptoms of attention-deficit hyperactivity disorder (ADHD) have been shown to be one such human factor that has a negative effect on driving ability (Jerome et al. 2006). A majority of this literature has been derived from self-report and on-road evaluation data (Jerome et al. 2006; Merkel et al. 2016; Randell et al. 2016). In comparison with their non-ADHD peers, those with ADHD are two to four times more likely to be involved in an accident (Bron et al. 2018; Sadek 2014). They also perform more poorly when completing on-road evaluations (Merkel et al. 2016; Randell et al. 2016), are more likely to suffer bodily injury due to being involved in an accident, receive speeding tickets, be found at fault, and have their license suspended (Barkley and Cox 2007; Barkley et al. 1996; Curry et al. 2017). These negative outcomes may be attributed to a variety of symptoms characteristic of ADHD, including heightened impulsivity (Jerome et al. 2006) and hyperactivity (Fischer et al. 2007). Clinical trials further show that inadequate concentration contributes to ADHD individuals' higher crash risk, but this may be improved with stimulant medication (Cox et al. 2004; Verster et al. 2008). Among those with ADHD, concentration difficulties may manifest themselves through unintentional mind wandering, or a tendency to be distracted from one's task due to insufficient monitoring capabilities (McVay and Kane 2010). Like inattention, mind wandering

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may be associated with crash risk (Galéra et al. 2012; Seli et al. 2015). However, its association with driving performance among those with ADHD has not received extensive attention in the literature.

In addition to self-report and on-road methods, simulator technologies represent an additional tool for assessing driving safety in clinical populations, including those with ADHD (Reimer et al. 2010; Weafer et al. 2008). In comparison with questionnaires, driving simulators are considered to have higher ecological validity and are not limited by pitfalls common across much of the field of psychology when using retrospective self-report measures (e.g., poor participant insight or memory, bias toward conveying oneself in an overly positive manner) (Schultheis and Rizzo 2001). Measures sensitive to the cognitive effects of ADHD have also shown some promise in predicting driving safety; however, these measures again lack ecological validity and may only be weakly correlated with actual driving performance (Barkley et al. 2002). Although on-the-road evaluations remain the "gold standard" when assessing driving safety, simulators represent a less dangerous means of obtaining a glimpse into an individual's driving, are less time-consuming, and do not require as much training to administer (Schultheis and Rizzo 2001). However, although simulators have been in use for several decades, the high costs associated with acquiring and running participants on full-body simulators have limited the number of research groups and institutions with access to simulator data. Top-end simulators, such as the National Advanced Driving Simulator-1 at the University of Iowa (www.nads-sc.uiowa.edu), cost in the millions of US dollars to develop and implement, and charge significant fees on a per-participant basis. These simulators offer a superior driving experience in terms of fidelity, control responsiveness, and complexity of motion platforms; however, they are also cost-prohibitive to most researchers. Even simulators described as being "low cost," such as one recently introduced at the University of Oulu in Finland, has a purchasing fee of approximately $28,000 (Koskela et al. 2011). With recent improvements in personal computer (PC) technology, PC-based simulators have been increasingly used for research purposes (Hassan and Gausemeier 2013). However, striking a balance between simulator fidelity and monetary cost has remained challenging.

Prior studies examining differences in driving simulator performance between ADHD individuals and their non-ADHD peers have yielded a variety of findings, mostly suggestive of a deleterious effect of ADHD status on driving. In comparison with those without ADHD, individuals with ADHD typically display increased speeding (Barkley et al. 1996; Fischer et al. 2007; Groom et al. 2015). Other aspects of driving demonstrate more mixed findings; for example, whereas some have identified differences in lane deviation (i.e., standard deviation of lateral position) (Fischer et al. 2007) and steering control (Barkley et al. 1996), others have not found such differences (Barkley et al. 2002; Groom et al. 2015). Additionally, while individuals with ADHD typically demonstrate poorer executive functioning (EF) capacities, disagreement persists as to whether these measures are useful for screening for impaired driving in those with ADHD, as EF measures may only be modestly associated with driving performance (Barkley et al. 2002).

The current study aimed to evaluate the sensitivity of a novel, less costly driving simulator to the detrimental effects of ADHD and related symptoms. In doing so, this study served as a pilot effort in exploring the simulator's potential utility for future use in both clinical and research contexts.

Methods

Participants and procedure

This research complied with the American Psychological Association Code of Ethics and was approved by the Louisiana State University Institutional Review Board. Informed consent was obtained from each participant. Participants were recruited from two sources: (1) the undergraduate psychology student pool and (2) a separate study examining the effects of white noise on cognitive performance in individuals with or without ADHD. Individuals recruited from the white noise study for the present one both self-reported history of ADHD and met criteria for the disorder based on a structured interview (i.e., the Diagnostic Interview for ADHD in Adults (DIVA)) administered as part of the white noise study (Kooij and Francken 2010; Roye 2017). Participants recruited via the undergraduate student pool were offered extra credit in their psychology courses in return for their participation. Participants recruited via the white noise study were not psychology students and were offered $15 as compensation. Inclusionary criteria included that participants be native English speakers and over the age of 18. Participants were also required to be licensed drivers and presently drive on a weekly basis at least five miles per week.

Data collection was completed in one 2-h session for each participant. Study investigators or trained undergraduate research assistants conducted all study procedures. All study sessions began with informed consent, followed by completion of the measures described below in the order that they appear. All participants from both groups completed the same study measures.

Measures

Driving simulator

The present study utilized a custom-built, personal computer-based racing simulator to measure driving performance. Assetto Corsa (AC) by Kunos Simulazioni was chosen given its realistic driving model, high-fidelity graphics, ease of data access, and lower price ($2368) compared to other simulators (Bugeja et al. 2017). The simulator was constructed to be consistent with that of a prior group utilizing AC (Stowe 2016), including an Intel Core i5-4690 processor, a Samsung 850 EVO solid state drive, 16 GB of memory, and an nVidia GeForce GTX970 4 GB SC gaming graphics card. The simulator ran on Microsoft Windows 7 Pro 64×. The display was a 40-inch class LED 1080p HDTV, with a Thrustmaster T500RS steering wheel and pedals (i.e., a throttle pedal and a brake pedal). AC was run through a STEAM account (store.steampowered.com). Data were collected using MoTec i2 Standard software. The simulator was loaned to study investigators from a biomedical research facility.

Prior to completing the driving task, participants were introduced to the simulator and its controls. Participants then completed a six-lap AC course, Vallelunga Club, which is relatively flat in terrain and has a well-defined, paved road. No other cars were present on the road. This course was available by default via AC and was not modified. Driving aids (e.g., racing line, traction control) and tire wear and tear were disabled. Participants were instructed to complete the course driving at a fast pace but one they felt comfortable at and in which they maintained full control of the vehicle. Outcome variables included lap times, ground speed (average, maximum, and standard deviation), number of tires off the track (average and maximum), throttle position (average and maximum), and brake position (average and maximum).

Self-report measures

Participants completed an online survey using Qualtrics software during the study appointment (www.qualtrics.com). The survey included collection of demographic information including ADHD status, as well as the questionnaires detailed below.

Participants completed several measures assessing subjective views of their driving behaviors and emotions. Participants completed the 24-item Driving Behavior Questionnaire (DBQ) as a measure of aberrant driving behaviors (Reason et al. 1990). The 14-item Driving Anger Scale (DAS) was also completed as a measure of anger experienced while behind the wheel (Deffenbacher et al. 1994) (Deffenbacher et al. 1994). Participants completed a one-item rating of their driving safety in comparison with others their age on a 5-point Likert scale from 1 ("Far less safe than others") to 5 ("Far more safe than others"). In addition, participants completed an objective driving history questionnaire measure, which assessed the frequency of their driving, as well as the number of driving accidents and other driving-related legal infractions committed within the previous year.

Participants completed two self-report measures assessing ADHD and executive functioning-related symptoms. The Barkley Adult ADHD Rating Scale-IV (BAARS-IV) was completed as a measure of inattentive and hyperactivity symptoms experienced during childhood and adulthood. Participants also completed the Barkley Deficits in Executive Functioning Scale (BDEFS) as a measure of everyday executive functioning abilities.

Cognitive assessment

Participants completed several computerized tasks assessing aspects of executive functioning and selective attention. These tasks were administered using E-Prime software (pstnet.com/products/e-prime). The n-back task is a working memory task in which participants respond if a visually presented stimulus matches the item seen two items prior (Snyder et al. 2015). The present study utilized mean accuracy across all trials as the outcome measure. The antisaccade task measures cognitive inhibition, requiring participants to maintain attention on a letter target while distracting stimuli are presented on the opposite side of a screen and identify the target letter as quickly as possible (Friedman et al. 2016). This study utilized the number of correct responses as the outcome measure. The number–letter switching task is a shifting task in which participants perform one of two tasks (i.e., categorizing number–letter pairs by either odd/even number or by vowel/consonant) based on the cue they observe prior to each trial (Snyder et al. 2015). Outcome variables on the number–letter switching task included average reaction time when the task switched, average reaction time when the task did not switch, and the difference between these two times (i.e., the cost). The sustained attention to response task (Robertson et al. 1997) is a measure of continuous attention and response inhibition in which participants respond to all target stimuli as quickly as possible while not responding to nontarget stimuli over an extended period. Outcome variables on the SART for this study's purposes included number of errors and average reaction time on target trials.

Analyses

Given group differences in sample sizes, Welch's t tests were used to assess differences between groups on all outcome variables, as well as continuously measured demographic variables (i.e., age). Cohen's d effect sizes of .2–.49 were considered a small effect, .5–.79 a medium effect, and .80 or above a large effect. Chi-squares were used to assess differences between groups on categorical demographic variables. Phi effect sizes of .1–.29 were considered a small effect, .30–.49 a medium effect, and .5 or above a large effect. Pearson's correlations were used to assess associations among self-report measures and between self-report measures and driving simulator variables. Significance was defined as $p < .05$. Manualized DIVA instructions (Kooij and Francken 2010) were used to categorize ADHD participants by subtype, and qualitative descriptors proposed by Barkley (2011) were used to designate symptom severity based on BAARS total scores in adulthood and childhood.

Results

Participant characteristics

Demographic information by group is included in Table 1. Welch's t tests revealed that the ADHD and non-ADHD groups differed in gender ($p < .05$) but not age ($p > .05$). Chi-squares revealed no differences in race or ethnicity ($p > .05$). Groups did not differ on number of years licensed, hours driven weekly, or miles driven weekly (all $p > .05$). Information regarding cognitive test scores by group is found in Table 2. Groups did not differ on any of the cognitive tasks (all $p > .05$).

In comparison with those without ADHD, those with an ADHD diagnosis reported greater symptoms of ADHD both presently [$t(85) = 5.42$, $p < .01$] and in childhood [$t(85) = 2.61$, $p < .05$]. They also reported greater difficulties with executive functioning [$t(85) = 2.00$, $p < .05$].

Within the ADHD group, a total of 56.3% had a predominantly inattentive subtype, 25.0% had a combined type, and 18.8% had a predominantly hyperactive–impulsive subtype. With regard to total adult ADHD symptom severity, a total of 6.2% of ADHD participants fell in the "moderately symptomatic" range and 92.8% fell in the "markedly or very symptomatic" range. With regard to child ADHD symptom severity, a total of 6.2% of ADHD participants fell in the "average" range, 25.0% fell in the "marginal symptomatic" range, 18.8% fell in the "borderline or somewhat symptomatic" range, 25.0% fell in the "mildly symptomatic" range, 18.8% fell in the "moderately symptomatic" range, and 6.3% fell in the "markedly or very symptomatic" range.

Table 1 Sample demographics

	ADHD group ($n = 16$)	Non-ADHD group ($n = 71$)	Full sample ($n = 87$)
Age (SD)	20.19 (2.7)	19.18 (1.6)	19.37 (1.9)
Gender (% female)*	6.9%	52.9%	41.6%
Race			
White	16.1%	51.7%	66.3%
Black	1.2%	17.2%	18.0%
Asian	1.2%	11.5%	12.4%
Other	0%	1.2%	1.1%
Ethnicity			
Hispanic/Latino	1.2%	5.7%	6.7%
Non-Hispanic/Latino	17.2%	75.9%	93.3%

*Significance at $p < .05$

Table 2 Descriptive statistics for cognitive test variables by group

	ADHD group mean (SD)	Non-ADHD group mean (SD)
2-Back task		
2-Back mean accuracy	5.33 (1.3)	5.67 (2.3)
Antisaccade task		
Accurate responses	20.27 (5.6)	20.06 (5.7)
SART		
Reaction time (s)	174.75 (67.8)	174.19 (89.5)
Number of errors	1.88 (3.7)	1.06 (1.8)
Number–letter switching task		
Switch reaction time (s)	1304.89 (263.0)	1336.90 (256.0)
Non-switch reaction time (s)	596.93 (96.4)	590.30 (122.8)
Switch cost (s)	– 707.96 (225.8)	– 746.61 (241.5)

SART sustained attention to response task

Group differences in simulator performance variables

Information regarding simulator variables by group is found in Table 3. Relative to non-ADHD participants, individuals with an ADHD diagnosis reached higher maximum ground speeds [$t(85) = 2.70$, $p < .05$], applied higher average pressure to the throttle [$t(85) = 2.54$, $p < .05$], and applied higher maximum amounts of throttle pressure [$t(85) = 3.63$, $p < .01$] and brake pressure [$t(85) = 3.61$, $p < .01$]. Groups did not differ in average ground speeds, average brake pressure, deviations in ground speed, average number of tires off the track, or total driving time (all $p > .05$).

Group differences in self-reported driving behaviors and ADHD symptoms

Information regarding self-reported driving behaviors and ADHD symptoms by group is found in Table 4. Relative to non-ADHD participants, individuals with an ADHD diagnosis reported being less safe drivers [$t(85) = -2.88$, $p < .01$]. They also reported more frequent mind wandering in their daily life [$t(85) = 3.622$, $p < .01$]. No group differences were found on self-reported driving history legal items, including accidents, accidents in which police were called to the scene, times pulled over by police, and traffic tickets received (all $p > .05$).

Relative to non-ADHD participants, those with an ADHD diagnosis reported more frequently experiencing lapses in attention while behind the wheel that are unlikely to endanger others [$t(85) = 2.23$, $p < .05$]. In contrast, no differences were found for frequency of committing other errors that may endanger others or intentionally engaging in unsafe driving behaviors that may endanger others (both $p > .05$). Groups did not differ on amount of anger experienced when behind the wheel ($p > .05$).

Table 3 Descriptive statistics for simulator variables by group

	ADHD group mean (SD)	Non-ADHD group mean (SD)
Lap time		
Lap 1 Time	187.90 (84.5)	203.96 (90.4)
Lap 2 Time	100.07 (18.6)	104.76 (27.7)
Lap 3 Time	97.80 (16.7)	97.62 (19.2)
Lap 4 Time	95.47 (23.5)	97.68 (28.8)
Lap 5 Time	94.10 (15.6)	93.39 (26.3)
Lap 6 time	91.77 (11.4)	92.11 (19.4)
Ground speed		
Average	67.14 (6.0)	65.84 (7.0)
Max*	151.98 (10.5)	142.69 (18.7)
SD	32.74 (6.7)	31.59 (6.9)
Number of tires off track		
Average	.55 (.3)	.50 (.3)
Max	4.00 (.0)	3.89 (.7)
Throttle position		
Average*	47.19 (8.5)	41.05 (9.8)
Max**	99.63 (.7)	95.89 (8.6)
Brake position		
Average	2.38 (.3)	1.85 (1.5)
Max**	92.94 (15.7)	73.67 (30.4)

*Significance at $p < .05$; **significance at $p < .01$

Correlations among measures

Associations between self-reported and simulator measures

Correlations between driving simulator and self-report data are found in Table 5. No associations between driving self-report measures and simulator variables were found. Greater mind wandering was associated with higher average throttle pressure ($r = .21$, $p < .05$), maximum throttle pressure ($r = .22$, $p < .05$), and maximum ground speed ($r = .25$, $p < .05$). No associations with simulator variables were found for self-reported childhood or adulthood ADHD symptoms, or executive functioning (all $p > .05$).

Associations among self-reported measures

Driving self-report measures were moderately to strongly correlated with one another (i.e., $r = .40$ to $r = .80$). Broadly, greater aberrant driving behaviors were associated with more severe ADHD symptoms experienced presently and in childhood (i.e., $r = .26$ to $r = .57$ across DBQ subscales). Greater self-reported lapses in attention behind the wheel and errors that may put other road users at risk were associated with greater executive dysfunction ($r = .24$ and $r = .36$, respectively); however, no relationship was found with intentional violations that may put others at risk ($p > .05$). Greater mind wandering was associated with greater aberrant driving behaviors broadly ($r = .35$ to $r = .57$) as well as driving anger ($r = .32$). Greater driving anger was associated with more severe ADHD symptoms presently ($r = .24$) but not in childhood. No other associations between symptom-related self-report and driving self-report measures were found (all $p > .05$).

Discussion

The current study sought to determine the relationships between driving behaviors, cognition, and ADHD symptoms, using a novel, cost efficient driving simulator. A

Table 4 Descriptive statistics for self-reported driving and ADHD symptoms by group

	ADHD group mean (SD)	Non-ADHD group mean (SD)
Driving self-report variables		
Self-reported driving history		
Driving safety**	3.44 (.6)	3.99 (.9)
Number of accidents (driver)	.56 (.6)	.30 (.6)
Number of accidents (police called)	.38 (.6)	.20 (.5)
Number of times pulled over	.50 (.8)	.44 (1.0)
Number of tickets	.50 (.8)	.23 (.6)
Number of years licensed	3.97 (3.0)	3.16 (1.5)
Number of hours driven weekly	5.80 (4.0)	7.81 (7.3)
Number of miles driven weekly	137.00 (26.0)	176.99 (60.4)
DBQ variables		
Lapses*	19.25 (5.8)	15.80 (4.3)
Errors	16.06 (3.5)	14.9 (4.5)
Violations	21.19 (6.4)	19.27 (5.1)
Total	56.50 (12.8)	49.96 (11.1)
DAS	42.13 (9.5)	42.70 (9.2)
ADHD self-report variables		
BAARS child inattention**	21.75 (6.8)	16.92 (5.5)
BAARS child hyperactivity*	20.3 (6.4)	16.75 (5.6)
BAARS child total score*	42.06 (11.9)	33.66 (10.)
BAARS adult inattention**	21.63 (4.4)	15.75 (4.4)
BAARS adult hyperactivity**	12.13 (2.3)	9.04 (2.5)
BAARS adult sluggish tempo	20.63 (3.7)	18.14 (4.7)
BAARS adult total score**	63.44 (8.8)	49.47 (11.3)
BDEFS total score*	41.13 (10.4)	41.13 (10.4)
Mind wandering		
ARCES total**	43.19 (6.7)	36.32 (7.6)

DBQ Driving Behavior Questionnaire, *DAS* Driving Anger Scale, *BAARS* Barkley Adult ADHD Rating Scale, *BDEFS* Barkley Deficits in Executive Functioning Scale, *ARCES* Attention-Related Cognitive Errors Scale

*Significance at $p < .05$; **significance at $p < .01$

sample of young adults with and without ADHD was recruited to test the relationships between self-reported and performance-based driving behaviors and ADHD symptom severity. Results from this pilot study indicate that individuals with ADHD differ from their non-ADHD peers on a subset of objective and subjective measures of driving performance. Specifically, individuals with ADHD administered greater average and maximum pressure on the throttle pedal throughout their laps, resulting in greater maximum speeds than their non-ADHD peers. These findings are consistent with previous studies demonstrating that individuals with ADHD are more likely to exceed the speed limit while driving (Merkel et al. 2016; Randell et al. 2016). While our study did not include a speed limit on the track, the participants were instructed to travel at a fast speed but also one with which they felt in full control of the vehicle.

Individuals with ADHD also demonstrated greater pressure on the brake pedals while driving. This finding is consistent with a previous study that demonstrated abrupt braking behaviors from individuals with ADHD, as compared to their non-ADHD peers (Merkel et al. 2016). Increased pressure on the brakes is not surprising, as the ADHD sample demonstrated greater pressure on the throttle and maximum speed, suggesting a need for greater deceleration. Additionally, abruptly braking may result from difficulties with both inattentive and impulsive symptoms in the moment, as individuals with ADHD report losing focus while driving (Jerome et al. 2006; Rosenbloom and Wultz 2011), causing them to react quickly or impulsively, in order to avoid collisions.

Individuals with ADHD applied greater pressure to both the throttle and brake pedals, which may contribute to greater maximum speeds and abrupt braking. Merkel et al.

Table 5 Correlations between self-reported ADHD symptoms, mind wandering, and simulator variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. BP: average	–																
2. BP: max	.603**	–															
3. GS: average	.072	.050	–														
4. GS: max	.609**	.398**	.206	–													
5. GS: SD	.526**	.364**	−.116	.784**	–												
6. Tires: average	.202	.216*	−.463**	.435**	.626**	–											
7. TP: average	.605**	.396**	.273*	.785**	.658**	.339**	–										
8. TP: max	.329**	.300**	.188	.515**	.524**	.253*	.508**	–									
9. Driving time	.196	.215*	−.430**	.148	.191	.477**	.102	.054	–								
10. ARCES	.069	.109	.078	.249*	.137	.101	.214*	.218*	.140	–							
11. BAARS child total	.032	−.073	.088	.014	−.034	−.059	.033	.039	.010	.445**	–						
12. BAARS adult total	.029	.012	.054	.096	−.061	−.020	.060	−.015	−.002	.550**	.648**	–					
13. BDEFS total	−.117	−.085	−.022	−.029	−.060	−.039	−.046	−.101	.010	.491**	.591**	.759**	–				
14. DBQ lapses	−.095	−.025	−.008	−.014	−.038	−.001	−.088	.091	.120	.567**	.319**	.334**	.237*	–			
15. DBQ errors	−.102	−.164	−.039	−.006	−.039	.057	−.108	.071	.178	.372**	.261*	.340**	.357**	.534**	–		
16. DBQ violations	.085	.050	.076	.079	−.127	−.046	.027	.178	.178	.346**	.246**	.307**	.181	.401**	.464**	–	
17. DAS total	.109	.029	−.134	.129	.074	.134	.160	.069	.199	.316**	.133	.238*	.136	.311**	.214*	.420**	–

BP brake position, *GS* ground speed, *Tires* number of tires off of the track, *TP* throttle position, *SD* standard deviation, *ARCES* Attention-Related Cognitive Errors Scale, *BAARS* Barkley Adult ADHD Rating Scale, *BDEFS* Barkley Deficits in Executive Functioning Scale, *DBQ* Driving Behavior Questionnaire, *DAS* Driving Anger Scale

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

(2016) suggest that individuals with ADHD are more likely to cause accidents while driving by demonstrating poor/risky driving behaviors, including speeding and lapses in attention, than those without ADHD (Merkel et al. 2016). Taken together, this suggests that individuals with ADHD may possess a “lead foot” driving profile, which can cause greater maximum speeds and a need for reduced stopping times, in order to compensate for some ADHD-associated driving behaviors (i.e., increased overall speed, inattention, etc.).

Differences between those with and without ADHD were also found on self-reported measures of driving behaviors and cognitive functioning. Specifically, individuals with ADHD reported greater lapses in attention when driving in their everyday lives, but did not differ from those with ADHD in self-reported unintentional but potentially dangerous driving errors, intentional violations that may put others at risk, or feelings of anger while driving. However, within the entire sample, current ADHD symptom severity was positively related to all of these self-reported driving measures. These findings are somewhat consistent with Groom et al. (2015), who noted that individuals with ADHD reported greater lapses in attention, violations, and being angry while driving, but no differences in driving errors (Groom et al. 2015). These findings suggest that ADHD symptom severity may directly influence an individual’s driving behaviors.

As might be expected, individuals with ADHD reported greater executive dysfunction and greater amounts of mind wandering throughout their day (Franklin et al. 2017; Seli et al. 2015). Similarly, within the entire sample, current ADHD symptom severity was positively related to greater executive dysfunction and greater amounts of mind wandering during daily life, a trait that also correlated with lapses in attention while driving. Moreover, within the entire sample, increased mind wandering was related to higher maximum and average throttle pressure while driving, along with having a greater maximum ground speed. Together, these driving behaviors are comparable to those exhibited within the ADHD sample, suggesting that maladaptive driving behaviors may be related to increased mind wandering, which is a common attribute of individuals with ADHD (Seli et al. 2015). Future studies with larger sample sizes could explore whether executive functioning and mind wandering mediate the relationship between ADHD and driving.

Although sample sizes similar to the present study have been used in studies of developmental disorders and driving (de Oliveira and Wann 2011; Groom et al. 2015; Merkel et al. 2016), the current sample size should still be considered a limitation. Results require replication with a larger sample size. There is also a procedural limitation to this study, as individuals with ADHD were requested to abstain from their medication prior to completing the study. However, medication adherence was not assessed on the day of testing, which may have interfered with findings. This is important because previous studies have demonstrated that stimulant medication use in ADHD populations may improve driving abilities (Barkley and Cox 2007). However, despite these limitations, relationships between self-reported information, and performance-based measures and self-reported driving behaviors appear consistent with the previous literature.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional review board and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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

References

Barkley RA (2011) Barkley adult ADHD rating scale-IV (BAARS-IV). Guilford Press

Barkley RA, Cox D (2007) A review of driving risks and impairments associated with attention-deficit/hyperactivity disorder and the effects of stimulant medication on driving performance. J Saf Res 38(1):113–128

Barkley RA, Murphy KR, Kwasnik D (1996) Motor vehicle driving competencies and risks in teens and young adults with attention deficit hyperactivity disorder. Pediatrics 98(6):1089–1095

Barkley RA, Murphy KR, Dupaul GJ, Bush T (2002) Driving in young adults with attention deficit hyperactivity disorder: knowledge, performance, adverse outcomes, and the role of executive functioning. J Int Neuropsychol Soc 8(5):655–672

Bron TI, Bijlenga D, Breuk M, Michielsen M, Beekman AT, Sandra J (2018) Risk factors for adverse driving outcomes in Dutch adults with ADHD and controls. Accid Anal Prev 111:338–344

Bugeja K, Spina S, Buhagiar F (2017) Telemetry-based optimisation for user training in racing simulators. Paper presented at the 2017 9th international conference on virtual worlds and games for serious applications (VS-games)

Castro C (2008) Human factors of visual and cognitive performance in driving. CRC Press, Boca Raton

Cox DJ, Merkel RL, Penberthy JK, Kovatchev B, Hankin CS (2004) Impact of methylphenidate delivery profiles on driving performance of adolescents with attention-deficit/hyperactivity disorder: a pilot study. J Am Acad Child Adolesc Psychiatry 43(3):269–275

Curry AE, Metzger KB, Pfeiffer MR, Elliott MR, Winston FK, Power TJ (2017) Motor vehicle crash risk among adolescents and young adults with attention-deficit/hyperactivity disorder. JAMA Pediatr 171(8):756–763

de Oliveira RF, Wann JP (2011) Driving skills of young adults with developmental coordination disorder: regulating speed and coping with distraction. Res Dev Disabil 32(4):1301–1308

Deffenbacher JL, Oetting ER, Lynch RS (1994) Development of a driving anger scale. Psychol Rep 74(1):83–91

Fischer M, Barkley RA, Smallish L, Fletcher K (2007) Hyperactive children as young adults: driving abilities, safe driving behavior, and adverse driving outcomes. Accid Anal Prev 39(1):94–105
Franklin MS, Mrazek MD, Anderson CL, Johnston C, Smallwood J, Kingstone A, Schooler JW (2017) Tracking distraction: the relationship between mind-wandering, meta-awareness, and ADHD symptomatology. J Atten Disord 21(6):475–486
Friedman NP, Miyake A, Altamirano LJ, Corley RP, Young SE, Rhea SA, Hewitt JK (2016) Stability and change in executive function abilities from late adolescence to early adulthood: a longitudinal twin study. Dev Psychol 52(2):326
Galéra C, Orriols L, M'Bailara K, Laborey M, Contrand B, Ribéreau-Gayon R, Fort A (2012) Mind wandering and driving: responsibility case-control study. BMJ 345:e8105
Groom MJ, Van Loon E, Daley D, Chapman P, Hollis C (2015) Driving behaviour in adults with attention deficit/hyperactivity disorder. BMC Psychiatry 15(1):175
Hassan B, Gausemeier J (2013) Concept for a task—specific reconfigurable driving simulator. Development 3:4
Jerome L, Segal A, Habinski L (2006) What we know about ADHD and driving risk: a literature review, meta-analysis and critique. J Can Acad Child Adolesc Psychiatry 15(3):105
Kooij J, Francken M (2010) Diagnostic interview for ADHD in adults 2.0 (DIVA 2.0). Adult ADHD, Diagnostic Assessment and Treatment, Pearson Assessment and Information BV, Amsterdam
Koskela K, Nurkkala V, Kalermo J, Järvilehto T (2011) Low-cost driving simulator for driver behavior research. Paper presented at the proceedings of the 2011 international conference on computer graphics and virtual reality, CGVR
McVay JC, Kane MJ (2010) Adrift in the stream of thought: the effects of mind wandering on executive control and working memory capacity. In: Handbook of individual differences in cognition. Springer, New York, NY, pp 321–334
Merkel RL Jr, Nichols JQ, Fellers JC, Hidalgo P, Martinez LA, Putziger I, Cox DJ (2016) Comparison of on-road driving between young adults with and without ADHD. J Atten Disord 20(3):260–269
National Highway Traffic Safety Administration (2018) US DOT announces 2017 roadway fatalities down. Retrieved from https://www.nhtsa.gov
Randell NJ, Charlton SG, Starkey NJ (2016) Driving with ADHD: performance effects and environment demand in traffic. J Atten Disord. https://doi.org/10.1177/1087054716658126
Reason J, Manstead A, Stradling S, Baxter J, Campbell K (1990) Errors and violations on the roads: a real distinction? Ergonomics 33(10–11):1315–1332
Reimer B, Mehler B, D'Ambrosio LA, Fried R (2010) The impact of distractions on young adult drivers with attention deficit hyperactivity disorder (ADHD). Accid Anal Prev 42(3):842–851
Robertson IH, Manly T, Andrade J, Baddeley BT, Yiend J (1997) Oops!' performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. Neuropsychologia 35(6):747–758
Rosenbloom T, Wultz B (2011) Thirty-day self-reported risky driving behaviors of ADHD and non-ADHD drivers. Accid Anal Prev 43(1):128–133
Roye S (2017) Assessing the impact of white noise on cognition in individuals with and without ADHD. (Unpublished master's thesis). Louisiana State University, Baton Rouge, Louisiana
Sadek J (2014) ADHD and driving a clinician's guide to ADHD. Springer, Berlin, pp 41–46
Schultheis MT, Rizzo AA (2001) The application of virtual reality technology in rehabilitation. Rehab Psychol 46(3):296
Seli P, Smallwood J, Cheyne JA, Smilek D (2015) On the relation of mind wandering and ADHD symptomatology. Psychon Bull Rev 22(3):629–636
Snyder HR, Miyake A, Hankin BL (2015) Advancing understanding of executive function impairments and psychopathology: bridging the gap between clinical and cognitive approaches. Front Psychol 6:328
Stowe J (2016) Initial build and installation of Assetto Corsa-based race simulator. Assetto Corsa Set-Up White Paper. Washington University in St. Louis
Verster JC, Bekker EM, de Roos M, Minova A, Eijken EJ, Kooij JS, Olivier B (2008) Methylphenidate significantly improves driving performance of adults with attention-deficit hyperactivity disorder: a randomized crossover trial. J Psychopharmacol 22(3):230–237
Weafer J, Camarillo D, Fillmore MT, Milich R, Marczinski CA (2008) Simulated driving performance of adults with ADHD: comparisons with alcohol intoxication. Exp Clin Psychopharmacol 16(3):251