ADHD, depression, and motor vehicle crashes: A prospective cohort study of continuously-monitored, real-world driving

Paula A. Aduen[a], Michael J. Kofler[b,*], Dustin E. Sarver[c], Erica L. Wells[b], Elia F. Soto[b], Daniel J. Cox[d]

[a] University of Virginia, Curry School of Education, United States
[b] Florida State University, Department of Psychology, United States
[c] University of Mississippi Medical Center, Center for Advancement of Youth, United States
[d] University of Virginia Health Sciences Center, Center for Behavioral Medicine Research, United States

ABSTRACT

ADHD is associated with automobile crashes, traffic fatalities, and serious road trauma, but it is unclear whether this risk is (a) driven by ADHD symptoms specifically, and (b) unique to ADHD or transdiagnostic across psychiatric disabilities, such as depression, that also have concentration problems as core symptoms. The current study provides the first prospective, continuously-monitored evaluation of crash risk related to ADHD symptoms, including the first on-road comparison of ADHD with another high-prevalence psychiatric disability (depression). A probability-based sample of 3226 drivers from six U.S. sites, including subsamples with self-reported ADHD ($n = 274$) and depression ($n = 251$), consented to have their vehicles outfitted with sophisticated data acquisition technologies to continuously monitor real-world, day-to-day driving from 'engine-on to engine-off' for 1–2 years (*Mean* = 440 consecutive days/driver, *Mean* = 9528 miles/driver). Crashes and near-crashes were objectively identified via software-based algorithms and double-coded manual validation (blinded to clinical status). Miles driven, days monitored, age, gender, education, and marital status were controlled. ADHD symptoms portended 5% increased crash risk per increase in symptom severity score (IRR = 1.05). This risk corresponded to approximately 1 biennial crash and 1 annual near-crash per driver with ADHD; crash risk doubled for drivers reporting ADHD symptom severity near the sample's maximum. Analyses based on self-reported clinical status indicated similarly elevated rates for ADHD (IRR = 1.46) and depression (IRR = 1.34) that may be related, in part, to both groups' inattention/concentration symptoms. Risk was not attenuated by ADHD usual treatment, but varied according to antidepressant medication status. Previous studies have significantly underestimated the risk for traffic crashes conveyed by ADHD and depression.

Motor vehicle crashes are a leading cause of death in the U.S. (Centers for Disease Control and Prevention, 2016) and occur disproportionately among individuals with high-prevalence psychiatric disorders such as ADHD (Fuermaier et al., 2015) and Depression (Bulmash et al., 2006). Converging evidence indicates that drivers with ADHD (Cox et al., 2011; Vaa, 2014; Barkley and Cox, 2007; Jerome et al., 2006) and drivers with Depression (Brunnauer et al., 2008; Wingen et al., 2006) have higher rates of adverse driving outcomes than healthy control drivers across a broad range of metrics that include crashes, citations, insurance claims, loss of licenses, serious crash-related injuries, and traffic fatalities (Barkley and Cox, 2007; Swensen et al., 2004; Aduen et al., 2015; Chang et al., 2014; Redelmeier et al., 2010). These findings have major public health implications when juxtaposed with the high prevalence of adult ADHD (4%) (Polanczyk et al., 2007) and Depression (7%–13%) (Hasin et al., 2005).

Meta-analytic evidence supports a robust link between ADHD (RR = 1.23–1.88), Depression (RR = 1.67–1.90) and motor vehicle crash risk (Vaa, 2003, 2014; Hill et al., 2017). However, the veracity of these estimates has been questioned due to uncontrolled confounds (Vaa, 2014) and the paucity of prospective, on-road data (Fuermaier et al., 2015; Merkel et al., 2016). As a result, there is significant evidence that the magnitude of these links has been both overestimated (Vaa, 2014) and underestimated (Jerome et al., 2006). For example, the most recent meta-analysis concluded that ADHD's true risk was modest, and conveyed in large part by extra-disorder factors including greater exposure, demographic risk factors (e.g., male gender), and/or concomitant transdiagnostic risk factors (Vaa, 2014). In contrast, emerging evidence suggests that ADHD's true risk may have been significantly

underestimated. Only one study has prospectively assessed ADHD's crash risk using objective, in-car monitoring of routine driving (*N* = 17), and found that over 60% of crashes involving drivers with ADHD were *not reported* to authorities/insurance companies (Cox et al., 2012). Similarly, additional evidence suggests that drivers with ADHD may systematically underreport their driving errors in self-report studies (Knouse et al., 2005; Wåhlberg and Dorn, 2015).

Official police/government records have been used to address these concerns, but are limited to crashes on public roads and decisions to report the crash (drivers), send an officer (police dispatch), and file an official report (officer) (McCartt and Solomon, 2004). Further, national registers and hospital database reviews have been limited to crashes that involve death or severe road trauma (Swensen et al., 2004; Chang et al., 2014). Simulator studies and standardized on-road driving tests address some of these limitations, but provide time-limited evaluation of driving skills under ideal conditions that may not correspond to day-to-day driving habits and in-car distractions (Brunnauer et al., 2008; Biederman et al., 2007; Barkley et al., 2005). In addition, fewer than 50% of studies report miles driven, despite the known association between exposure and crash risk (Cox et al., 2011). Finally, the correspondence between retrospective self-report and prospective crash risk is unknown.

An additional limitation of this literature is the paucity of empirical studies directly comparing multiple forms of high prevalence psychiatric disability (Jerome et al., 2006). These comparisons are particularly critical for understanding ADHD-related risk given the nonspecific nature of core ADHD symptoms (Fuermaier et al., 2015; Aduen et al., 2015), and questions regarding the extent to which ADHD specifically, or psychiatric disability in general, portends risk for adverse driving outcomes (Vaa, 2014). For example, Depression is another high prevalence psychiatric disability associated with both attention/concentration problems and increased crash risk (Wingen et al., 2006; Austin et al., 2001; Wickens et al., 2014). In the only empirical study to date, to our knowledge, that directly compared ADHD and Depression, Aduen and colleagues (2015) found that only ADHD was associated with multiple collisions and violations, whereas only Depression was associated with self-reported injury following a collision. However, that study relied exclusively on retrospective self-report data, despite concerns regarding the reliability of self-reported driving outcomes for these groups (Knouse et al., 2005; Wåhlberg and Dorn, 2015).

The current study prospectively follows the large cohort of drivers from Aduen et al. (2015) and is well positioned to address issues related to both overestimation and underestimation of crash risk via (1) robust control for exposure and multiple risk factors for crashes (Di Milia et al., 2011) that are also correlates of ADHD (Cox et al., 2011; Jerome et al., 2006), and (2) large-scale, continuous-monitoring of adverse outcomes during routine driving as a function of ADHD symptom severity and clinical status. This multisite sample of 3226 drivers was surveyed for ADHD symptoms, psychiatric status, and prior crash involvement. Their driving was then monitored continuously using in-car technologies that recorded, on average, 9500 miles of routine driving from 'engine-on to engine-off' over a span of 440 consecutive days per driver (totaling > 5.5 million recorded trips).

Primary analyses focused on prospective crash risk portended by ADHD symptom severity. Exploratory analyses examined risk as a function of clinical group designations identified at study entry (Aduen et al., 2015), medication treatment assessed at study entry and exit, and correspondence between retrospective self-report and prospective crash risk. We hypothesized that ADHD symptom severity would portend increased risk for future adverse driving outcomes (Cox et al., 2011; Vaa, 2014; Barkley and Cox, 2007). Based on the retrospective self-report data from this sample (Aduen et al., 2015), we expected the exploratory clinical group analyses to show increased crash risk for ADHD but not Depression. We also expected medication to attenuate crash risk, such that medicated drivers with ADHD/Depression would show lower crash risk relative to unmedicated drivers with ADHD/

Depression (Barkley and Cox, 2007; Brunnauer et al., 2008; Wingen et al., 2006; Cox et al., 2012). Finally, we expected retrospective self-report to predict prospective crash risk for healthy control drivers, but made no predictions regarding these relations among drivers with ADHD and Depression given the paucity of previous research.

1. Method

1.1. Design and overview

Probability-based sampling was employed to obtain a representative sample of 3600 licensed drivers (3226 were followed prospectively, including 2329 of the 2354 drivers assigned to a clinical/comparison group by Aduen et al. (2015). Drivers were oversampled for younger and older drivers across 6 U.S. sites: Florida (Tampa), Indiana (Bloomington), North Carolina (Durham), New York (Buffalo), Pennsylvania (State College), and Washington (Seattle). Sample demographics are shown in Table 1, and were controlled in all analyses based on prior evidence that each covariate is associated with adverse driving outcomes (age, gender, education/socioeconomic status, marital status, miles driven, and days of study monitoring) (Barkley et al., 2005; Whitlock et al., 2004). Detailed sample descriptives and population-based comparisons with U.S. licensed drivers are provided in Antin et al. (2015). Comparisons indicate close approximation to U.S. drivers for the sample. Technical reporting of the Strategic Highway Research Program Naturalistic Driving Study (SHRP-2) study design, recruitment, and methodological plans are found in Antin et al. (2011).

1.2. Continuous monitoring and event triggers

Each driver's car was outfitted with five high-speed video cameras, speed/brake monitors, accelerometers, and GPS to continuously capture routine driving from engine-on to engine-off for 1–2 consecutive years per driver (5,512,900 individual trips that occurred between 2010 and 2013) (Antin et al., 2011). Software-based trigger algorithms with 100% double-coded manual validation identified 4254 safety-critical events (SCEs; 1549 crashes, 2705 near-crashes). These software-based algorithms used kinematic and behavioral signatures previously identified as present with high probability during crashes (e.g., longitudinal deceleration < −0.65 g, lateral acceleration > 0.75 g) (Antin et al., 2011, 2015). Detailed data reduction methods, software-based trigger algorithms and validation, vehicle sensor calibration, data reductionist training, and reliability are provided in Hankey et al. (2016).

All SCEs were verified by comparing event videos with pre-recorded index images to ensure the consented participant was driving. Manual video review then verified if an SCE occurred. Verified events were coded by extensively trained data reductionists (100% SCEs coded by ≥ 2 coders; reliability = 91%) (Antin et al., 2011, 2015). Coders were blind to driver clinical status (Antin et al., 2011).

1.3. Prospective driving outcomes

Primary outcomes included number of *crashes* (SCEs involving any contact between participant vehicle and fixed or moving object, at any speed where kinetic energy is measurably transferred or dissipated) and *near-crashes* (SCEs requiring a rapid, evasive maneuver by participant vehicle to avoid an imminent crash) recorded during prospective on-road monitoring.

1.4. Barkley Adult ADHD Quick Screen (BAQS)

After enrollment, all participants completed the BAQS, a 6-item self-report questionnaire that assesses ADHD symptoms in adults on a 4-point scale (0 = never/rarely, 1 = sometimes, 2 = often, 3 = very often; range = 0–18). Scores are summed across the six items and correlate 0.97 with scores from full, 18-item DSM-IV symptom

Table 1
Sample demographics.

	Overall Sample (N = 3226)		ADHD (N = 274)		Depression (N = 249)		Healthy Control (N = 1806)		Clinical Subgroup Chi-square
	M	SD	M	SD	M	SD	M	SD	
Miles Driven	9527.9	7315.8	9874.2	7346.9	9716.6	6846.1	9390.9	7510.0	p = .53, ns
Days Monitored	440.49	210.65	423.39	202.68	442.17	210.34	439.85	213.36	p = .46, ns
BAQS ADHD Score	3.20	2.18	7.43	2.57	3.39	1.63	1.86	1.01	p < .0005
Percent involved in									
No crashes	70.3%		58.8%		64.7%		72.8%		p < .001
Single crash	19.9%		23.4%		21.7%		19.1%		
Multiple crashes	9.8%		17.9%		13.7%		8.1%		
No near-crashes	61.7%		52.2%		52.2%		64.4%		p < .001
Single near-crash	21.7%		25.5%		24.5%		20.8%		
Multi. near-crashes	16.6%		22.3%		23.3%		14.8%		
	N	%	N	%	N	%	N	%	
Age Group									p < .005
16-17	258	8.0	40	14.7	13	5.2	126	7.0	
18-20	520	16.1	71	26.0	39	15.7	248	13.8	
21-25	597	18.5	77	28.2	53	21.3	280	15.5	
26-35	327	10.1	25	9.2	25	10.0	192	10.6	
36-50	349	10.8	25	9.2	38	15.3	198	11.0	
51-65	383	11.9	11	4.0	37	14.9	234	13.0	
66-75	345	10.7	12	4.4	28	11.2	213	11.8	
75 +	442	13.7	12	4.4	16	6.4	312	17.3	
Not reported	5	0.2	1	0.004	0	0.0	3	0.002	
Gender									p < .005
Male	1537	47.6	131	48.3	75	30.4	900	50.3	
Female	1661	51.5	140	51.7	172	69.6	890	49.7	
Not Reported	28	0.9	3	0.01	2	0.001	16	0.001	
Education									p < .005
Some high school	271	8.4	39	14.3	14	5.7	126	7.0	
H.S. graduate	1241	38.5	118	43.2	100	40.5	660	36.8	
College degree +	1692	52.4	116	42.5	133	53.8	1006	56.1	
Not reported	22	0.7	1	0.003	2	0.001	14	0.008	
Marital Status									p < .005
Not Married	1989	61.7	211	77.9	162	65.3	1054	58.9	
Married	1207	37.4	60	22.1	86	34.7	734	41.1	
Not reported	30	0.9	3	0.01	1	0.004	18	0.001	
Annual Income									p = .04
Under $29K	556	17.2	60	21.9	52	20.9	282	15.6	
$30K to $39K	378	11.7	26	9.5	27	10.8	233	12.9	
$50K to $69K	537	16.6	36	13.1	39	15.7	297	16.4	
$70K to $99K	551	17.1	36	13.1	44	17.7	316	17.5	
$100K to $149K	462	14.3	37	13.5	36	14.5	258	14.3	
$150K or higher	219	6.8	28	10.2	14	5.6	133	7.4	
Not reported	523	16.2	51	18.6	37	14.9	287	15.9	

Note: *BAQS = Barkley Adult ADHD Quick Screen.*

checklists (Barkley et al., 2010). Psychometric support includes high internal consistency ($\alpha = 0.90$) and concurrent validity for self-reported ($r = 0.97$) and other-report ($r = 0.68$) 18-item ADHD symptom checklists. The predictive validity is adequate for self-reported ($r = 0.87$) and other-reported impairment ($r = 0.67$), in addition to high sensitivity (0.93) and specificity (0.99) for differentiating adults with ADHD from neurotypical adults based on a clinical cut-off score of ≥ 7 (Barkley et al., 2010).

1.5. Clinical groups

1.5.1. Overview

Exploratory clinical group analyses were conducted using the diagnostic groups defined for this sample at study entry (Aduen et al., 2015). Briefly, Aduen et al. (2015) identified 275 drivers with ADHD and 1828 drivers with no known psychopathology (Healthy Controls) based on self-reported current clinical status and symptoms at study entry. They also identified 251 drivers with Depression, who are

included here to provide the first on-road comparison of ADHD with another high-prevalence psychiatric disorder (Kessler and Bromet, 2013) associated with attention/concentration problems (Austin et al., 2001; Paelecke-Habermann et al., 2005) and adverse driving outcomes (Wickens et al., 2014). Clinical group comparisons were conducted using these psychiatric diagnoses (Aduen et al., 2015), and are considered exploratory because the naturalistic study design precluded clinical interviewing or tracking illness course/treatment efficacy during the prospective monitoring of driving outcomes.

1.5.2. Group assignment

Group membership at study entry was defined by Aduen et al. (2015) from an initial sample of 3259 participants as follows: Participants were included in the *ADHD Group* with a positive BAQS screen (≥ 7) and/or self-reported ADHD, alone ($n = 229$) or comorbid with anxiety ($n = 46$; total $n = 275$). Participants with positive BAQS screens who reported other clinical disorders but not ADHD ($n = 52$) were excluded from the ADHD group as recommended because 83% of

mood disorders screen positive on the BAQS (Barkley et al., 2010). Participants were included in the *Depression Group* if they endorsed Depression, alone (*n* = 170) or comorbid with anxiety (*n* = 81),[1] but not ADHD (total *n* = 251); no BAQS criteria were set for the Depression Group. Individuals with self-reported anxiety were included given its high comorbidity with both adult ADHD and Depression (Barkley et al., 2010). Individuals were assigned to the *Healthy Control Group* (no known psychopathology) based on negative BAQS screen (< 4) and no self-reported psychological diagnoses (*n* = 1828). Participants were excluded from all groups if they self-reported personality, psychotic, or bipolar disorders (*n* = 32). The remaining 821 cases were excluded for failing to meet any group criteria (i.e., no self-reported Depression and BAQS scores of 4–6 that fell between the Healthy Control maximum and ADHD minimum).

1.6. Psychiatric treatment

ADHD and antidepressant medications were queried at study entry and exit (Antin et al., 2011) and used as a proxy for active treatment (Cox et al., 2012). Consistent with epidemiological estimates (Kessler et al., 2006; Harman et al., 2015), 20.8% and 61.0% of drivers with ADHD and Depression, respectively, reported disorder-specific medication treatment at one or both time points. Exploratory analyses were conducted by subdividing the ADHD and Depression groups into mutually exclusive categories: *Unmedicated* (no reported medication that treats their identified disorder at either time point), *Started* (reported at exit but not entry), *Stopped* (reported at entry not exit), and *Medicated* (reported at both time points).

Cell sizes were sufficient for exploratory analyses of antidepressant time course for the Depression group (Unmedicated = 99; Started = 98; Stopped = 24; Medicated = 30). ADHD medication was dichotomized based on medication at either time point (No = 218; Yes = 57) due to insufficient cell counts (Unmedicated = 218; Started = 43; Stopped = 12; Medicated = 2). The naturalistic study design precluded monitoring of perceived medication efficacy, emergent effects, or timing in relation to crashes. Nevertheless, these analyses reflect the most extensive examination to date of the protective effects of medication treatment against crashes during real-world, day-to-day driving.

1.7. Data analysis overview

Negative binomial regressions predicted the maximum likelihood (MLE) conditional probability (incident rate ratios; IRR with Wald 95%CIs) (Valentine et al., 2015) of crash and near-crash counts as a function of ADHD symptom severity scores, controlling for miles driven, days of continuous monitoring (exposure), age, gender, education, and marital status. Separate models were run for crashes and near-crashes. To aid interpretation, IRRs are supplemented with estimates of annual risk per driver by computing estimated marginal means with time set to 365.25 days and miles driven set to the U.S. national average of 15,000 annual miles driven (National Center for Statistics and Analysis, 2015).

Exploratory analyses repeated these models, first substituting the categorical clinical groups (Aduen et al., 2015) (ADHD, Depression, Healthy Control) for BAQS scores, and finally subdividing the ADHD

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[1] Self-reported anxiety did not predict crashes or near-crashes when added as an exploratory predictor in the clinical group models below (all *p* > .79; all 95%CIs included 1.0), and its inclusion did not change the significance or interpretation of any results. Exploratory analyses indicated also that crash and near-crash rates did not vary significantly (all *p* > .34; all 95%CIs included 1.0) as a function of the criteria for ADHD group membership (*n* = 48 self-reported an ADHD diagnosis but did not meet the BAQS cutoff, *n* = 169 met the BAQS cut-off but did not self-report an ADHD diagnosis, *n* = 58 self-reported an ADHD diagnosis and met the BAQS criteria). Results are therefore reported for the combined ADHD group and without anxiety included to most closely match the retrospective report from this sample from Aduen et al. (2015).

and Depression groups by medication status.

All models were superior to the null model (all omnibus likelihood ratio $\chi^2[14] \geq 218.01$, all *p* < .0005) and demonstrated adequate goodness-of-fit (all $\chi^2/df = 1.07–1.24$). The dispersion coefficient (negative binomial) was significantly greater than 0.0 for all models (all 95%CIs exclude 0.0), supporting use of the negative binomial over Poisson distribution models.

1.8. Ethics statement

Participants gave informed consent before participating. Participants were protected by a national Certificate of Confidentiality and not required to surrender study-related materials to authorities (Antin et al., 2011).

2. Results

2.1. Preliminary analyses

Missing data ranged from 0.1 to 0.9% for gender, age, education, and marital status and did not vary by clinical group (*p* = .60), supporting Missing at Random (MAR) assumptions. Education served as a proxy for socioeconomic status (Di Milia et al., 2011). Sample retention was excellent: 3226 cases (89.6%) were followed prospectively and included in analyses. Of the 2354 drivers assigned to a clinical or control group at study entry (Aduen et al., 2015), 2329 (98.9%) were retained including 274 of 275 drivers with ADHD (99.6%), 249 of 251 drivers with Depression (99.2%), and 1806 of 1828 Healthy Control drivers (98.8%). These groups did not differ in miles driven (mean = 9527.90 miles; *p* = .53), days of study participation (mean = 440.49 days; *p* = .46), or performance on a driving knowledge questionnaire (mean$_{correct}$ = 79.74%; *p* = .14). Group differences in demographics are detailed in Aduen et al., 2015, and include differences in gender (more females in the Depression group), age (ADHD overrepresented in the youngest age groups and underrepresented in the oldest age groups), marital status (ADHD drivers less likely to be married), and education (ADHD drivers less likely to have a high school diploma or college degree). These demographic variables were included as covariates in all subsequent analyses.

2.2. ADHD symptoms

Greater ADHD symptoms at study entry portended 5%–6% increased risk *per increase in symptom severity score* for crashes (IRR = 1.05, 95%CI = 1.02–1.09, *p* < .0005), and near-crashes
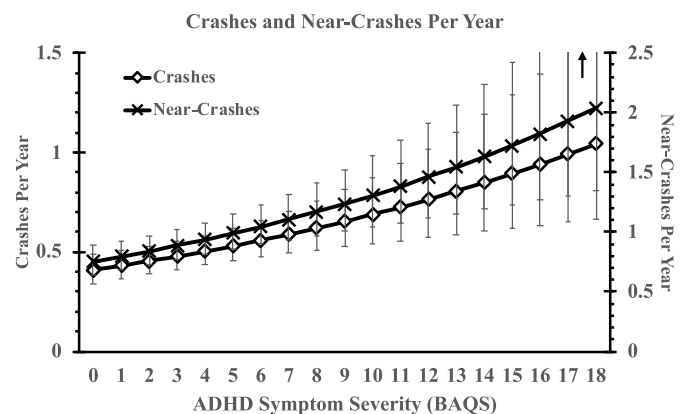

Fig. 1. Crash and near-crash risk as a function of BAQS ADHD symptom severity scores. Values reflect estimated marginal means for incidents per year, controlled for age, gender, education, and marital status. Per year was defined for days of continuous monitoring = 365.25 and total miles driven = 15,000. Error bars reflect 95% Wald confidence intervals (CIs).
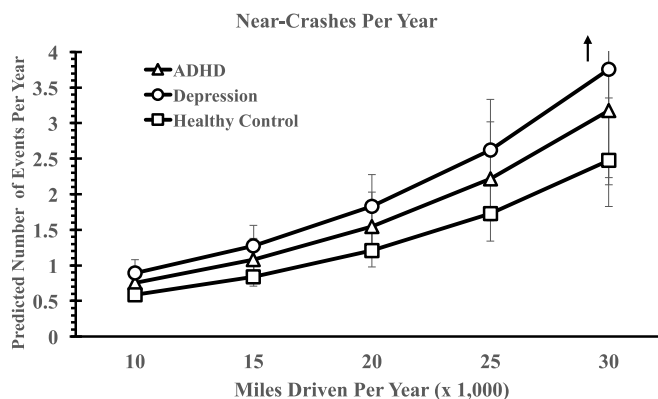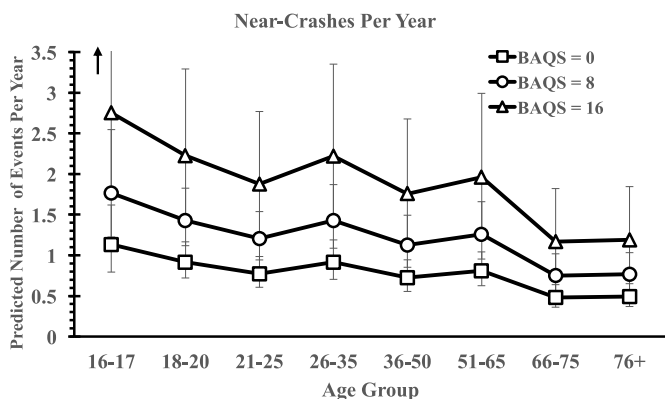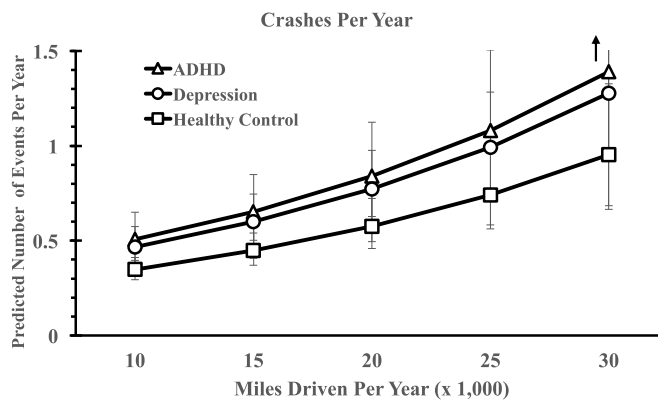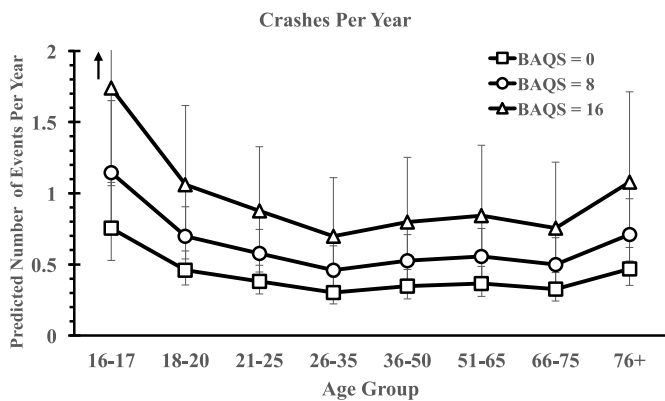
Fig. 2. Crash and near-crash risk as a function of ADHD symptoms (BAQS) and age group. BAQS scores were selected to be representative and equidistant. BAQS = 0 indicates no ADHD symptoms, BASQ = 8 exceeds the clinical cut-off for ADHD of > 7, and BAQS = 16 indicates high severity ADHD symptoms. Values reflect estimated marginal means for incidents per year, controlled for gender, education, and marital status. Per year was defined for days of continuous monitoring = 365.25 and total miles driven = 15,000. Error bars reflect 95% Wald CIs.

Fig. 3. Crash and near-crash risk as a function of clinical group and exposure (miles driven per year), controlled for age, gender, education, and marital status. Values reflect estimated marginal means for incidents per year, defined for days of continuous monitoring = 365.25. Error bars reflect 95% Wald confidence intervals.

(IRR = 1.06, 95%CI = 1.03–1.09, $p < .0005$). Annual number of expected crashes/near-crashes as a function of BAQS ADHD symptom severity score is depicted in Fig. 1. Notably, risk increases *per ADHD symptom severity endorsement*[2]; for example, a BAQS score of 17 predicts approximately 1 annual crash *per driver* (0.99 crashes/driver), while a BAQS score of 0 predicts 1 crash per 2.4 drivers (0.41 crashes/driver). Fig. 2 shows these estimates as a function of age group.

2.3. Clinical groups

ADHD designation at study entry portended 46% increased risk for crashes (IRR = 1.46, 95%CI = 1.17–1.83, $p = .001$) and 28% increased risk for near-crashes (IRR = 1.28, 95%CI = 1.04–1.58, $p = .02$). These data correspond, on average, to 0.65 annual crashes and 1.08 annual near-crashes per driver with ADHD. Figs. 3 and 4 show these estimates as a function of miles driven and age groups.

Depression at study entry portended 34% increased risk for crashes (IRR = 1.34, 95%CI = 1.05–1.71, $p = .02$) and 52% increased risk for

near-crashes (IRR = 1.52, 95%CI = 1.22–1.88, $p < .0005$). These data predict, on average, 0.60 annual crashes and 1.28 annual near-crashes per driver with Depression (Figs. 3–4). Drivers with ADHD did not significantly differ from drivers with Depression on crashes (IRR = 0.92, 95%CI = 0.68–1.25, $p = .59$) or near-crashes (IRR = 1.18, 95%CI = 0.90,1.56, $p = .23$).

2.4. Treatment status

2.4.1. ADHD

Exploratory analyses indicated that medication treatment for ADHD did not attenuate driving risk, as evidenced by increased crash risk for both untreated (IRR = 1.36, 95%CI = 1.06–1.75, $p = .02$) and treated (IRR = 1.86, 95%CI = 1.22–2.82, $p = .004$) drivers with ADHD relative to Healthy Control drivers. The treated and untreated ADHD subgroups did not differ (IRR = 1.33, 95%CI = 0.85–2.08, $p = .21$).

2.4.2. Depression

Results indicated reduced crash risk for medicated drivers with Depression, such that crash risk relative to Healthy Controls was detected only for the subgroup who discontinued antidepressants during the study (IRR = 2.35, 95%CI = 1.29–4.27, $p = .005$; all other subgroups $p \geq .24$). Drivers with Depression who discontinued medication also showed increased risk relative to unmedicated drivers with Depression (IRR = 2.05, 95%CI = 1.13–3.71, $p = .02$; all other between-subgroup comparisons $p > .23$).

2.5. Assessing crash risk: retrospective self-report vs. prospective monitoring

A final comparison was made by comparing the retrospective self-

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[2] *Per ADHD symptom severity endorsement* refers to an increase of 1 point on the BAQS (e.g., a change from 'sometimes' to 'often' on a single item). The range of BAQS scores in the sample was 0–17 (0–18 possible). A BAQS score of 0 reflects responses of never/rarely for all 6 items, whereas BAQS = 17 occurs when 5 of 6 symptoms occur very often, and 1 symptom occurs often. A BAQS score of 8 would exceed the questionnaire's clinical screening cutoff of 7, and could be obtained via several item endorsement combinations (e.g., endorsements of Often on 4 items and Never on the remaining two items, endorsements of Often on 2 items and Sometimes on the remaining 4 items). This score of 8 predicts 0.62 crashes (1 crash per 1.61 drivers) and 1.17 near-crashes per year.
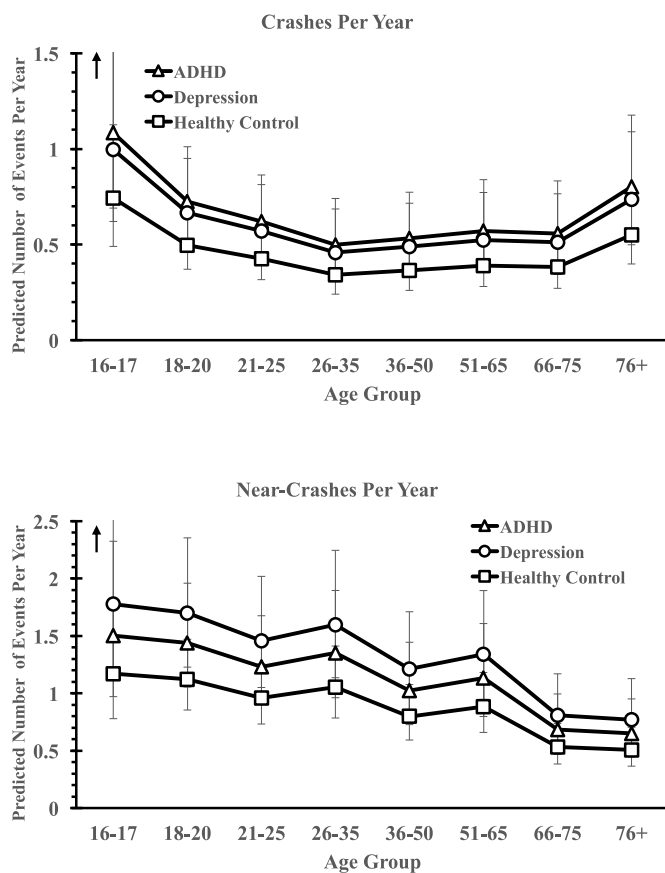
Fig. 4. Crash and near-crash risk as a function of clinical group and age group, controlled for age, gender, education, and marital status. Values reflect estimated marginal means for incidents per year, defined for days of continuous monitoring = 365.25 and miles driven = 15,000. Error bars reflect 95% Wald confidence intervals.

report data for this sample at study entry from Aduen et al. (2015) with the current study's prospective in-car monitoring. Partial correlations adjusted for miles driven, days of continuous monitoring, and driver demographics indicated that self-reported crash counts at study entry predicted crash counts during prospective monitoring for healthy control drivers ($r = 0.10$, $p < .0005$, $n = 1743$), but were poor predictors of prospectively-identified crashes for drivers in the ADHD ($r = -0.002$, $p = .98$, $n = 260$) and Depression groups ($r = -0.01$, $p = .85$, $n = 236$).

3. Discussion

The current study was the first prospective, continuously-monitored assessment of real-world crash risk as a function of ADHD symptoms, controlling for a host of established risk factors (Mannuzza et al., 1993). Prospective monitoring indicated a robust association between ADHD symptoms and adverse driving outcomes. The 5%–6% increased risk per ADHD symptom severity endorsement indicates that, on average, drivers who screen positive for ADHD are expected to have at least one biennial crash and one annual near-crash. This risk increases substantially as ADHD symptom severity increases, and doubles to predict approximately one crash per year for drivers reporting the most severe ADHD symptoms. Similarly, ADHD clinical status at study entry portended large magnitude risk for experiencing a crash (IRR = 1.46). Examination of the confidence intervals indicates that these estimates were higher than expected based on the most recent meta-analysis (RR = 1.23) (Vaa, 2014). Thus, our dimensional and categorical findings confirm that ADHD portends adverse driving outcomes (Fuermaier et al., 2015; Cox et al., 2011; Vaa, 2014; Jerome et al., 2006), and

extends previous findings by suggesting that this risk is higher than previously estimated at both the symptom and clinical group levels.

Importantly, however, this risk did not appear unique to ADHD, but occurred at elevated rates for drivers with Depression. Depression is another high-prevalence psychiatric disability associated with attention/concentration problems (Hill et al., 2017; Austin et al., 2001; Wickens et al., 2014; Paelecke-Habermann et al., 2005), and this group also reported elevated ADHD symptoms relative to controls in the current study. We propose both inattentive and impulsive/hyperactive behavior as potential transdiagnostic mechanisms, given their status as core symptoms of both ADHD and Depression (reified for the latter as 'concentration problems' and 'psychomotor agitation observable to others') (Fuermaier et al., 2015; Bulmash et al., 2006; Austin et al., 2001). Combined with the finding that crash risk increases proportionately with each increase in ADHD symptom severity (Fig. 1), these findings suggest that symptom frequency/severity may be more important than clinical status *per se* when assessing motor vehicle crash risk. At the same time, drivers with Depression may have been somewhat better able to avoid imminent crashes than drivers with ADHD (near-crash: $IRR_{Depression} = 1.28$ vs. $IRR_{ADHD} = 1.52$). Beyond the elevated but less severe ADHD symptoms exhibited by the Depression group, this result suggests potential disorder-specific differences in successfully recovering from presumed attentional lapses (Chang et al., 2014; Redelmeier et al., 2010) in time to avoid an imminent crash.

The association between Depression and crash risk appears inconsistent with retrospective self-report from this sample (Aduen et al., 2015), which documented this risk for ADHD but not Depression. The reason for this incongruence is not clear, but may be related to the overall poor correspondence between prior crashes and future crashes among drivers in the Depression and ADHD groups. Alternatively, exploratory analyses linked crash risk specifically to members of the Depression group who discontinued antidepressants during prospective monitoring. Medication results must be considered tentative, but protective effects of antidepressant treatment (Wingen et al., 2006) could explain this discrepancy given that these drivers were by definition taking medication when reporting prior crashes at study entry. We also considered Depression-specific explanations, but these appeared unlikely given evidence that these drivers appraise their driving performance more negatively than other drivers (Dorn and Matthews, 1995; Thames et al., 2011). Notably, the poor predictive validity of self-reported crashes for both clinical groups indicates that patient education is warranted irrespective of patients' self-reported crash history (i.e., self-reported safe driving is not a protective factor against future crashes for drivers with ADHD and Depression).

Medication was not associated with reduced risk for drivers with ADHD, with relatively wide confidence intervals that limit comparative statements regarding crash risk between medicated and unmedicated ADHD subgroups. Although there is evidence that certain psychostimulant formulations may increase crash risk in certain environments (Merkel et al., 2016; Randell et al., 2016), placebo-controlled studies are consistent in documenting reduced crash risk when medication is metabolically active (Merkel et al., 2016; Cox et al., 2012). Because ADHD medication has well-documented benefits for motor vehicle driving (Chang et al., 2017), the equivocal results for ADHD medication may reflect inconsistent adherence, interactions between unmedicated symptom severity and treatment status, and/or driving events that occurred when medication was not metabolically active (Cox et al., 2011; Barkley and Cox, 2007). Alternatively, the trend toward increased risk in medicated drivers may reflect effects of unmeasured factors rather than causes, such that 75% of medicated drivers with ADHD ($n = 43$ of 57) began treatment during the study monitoring period.

For the Depression group, the higher prevalence of medication treatment allowed us to separate medication status based on time course. We found that the increased risk for crashes was seen exclusively for drivers who discontinued antidepressant treatment during the study (IRR = 2.35). To our knowledge, there have been no

controlled studies documenting vehicular crash rates among patients who discontinue antidepressants. In the absence of such data, we suggest that the current findings call for patient education and routine consideration of driving risk during treatment planning – particularly when patients discontinue antidepressant medication.

3.1. Limitations

The current study was the first to prospectively track crash risk as a function of ADHD symptoms in a large sample of drivers using continuous, on-road monitoring. The following caveats must be considered. ADHD symptom severity was based on a well-validated ADHD screening measure (93% sensitivity, 99% specificity) (Barkley et al., 2010) whereas clinical group assignment was based on self-reported current diagnosis rather than gold-standard psychiatric interviewing. We were unable to track symptom course during prospective vehicle monitoring, and the proportion of females in the ADHD group (51%) was somewhat higher than expected based on current prevalence estimates. Although these methods are comparable to other large-scale epidemiological studies (Chang et al., 2014), generalization is limited to clinically- rather than research-defined ADHD and Depression (Jerome et al., 2006). Thus, while the results exhort patient education and consideration of driving risk in treatment planning, implications for putative etiological mechanisms are less clear. Participants were protected by a national Certificate of Confidentiality; thus, correspondence with police, hospital, and/or Department of Motor Vehicle record keeping is unknown.

Further, we were unable to track the course of Depression during prospective monitoring. Epidemiological evidence indicates that 20% of Depression cases are chronic across the two-year period covered in the current study (Spijker et al., 2002), and an additional 33%–50% experience recurrent episodes in a given year (Hasin et al., 2005). Nevertheless, the proportion of these drivers who were depressed and/or medicated at the time of a crash/near-crash is unknown, and uncertainty regarding medication and symptom time course precludes causal attributions. Still, epidemiological studies frequently use prescription data as a proxy for active treatment (Wingen et al., 2006; Merkel et al., 2016). For clinical practice, we interpret these findings to indicate that clinicians should educate patients regarding crash risk irrespective of self-reported crash history and potential symptom remission.

Finally, we were unable to examine proximal risk factors for crashes, such as *in situ* driver behaviors, cell phones, alcohol and substance use, or whether medication was active at the time of a crash. Thus, additional work is needed to identify the mechanisms by which ADHD confers crash risk (e.g., increased risk for substance use is a known outcome of ADHD as well as a risk factor for crashes) (Barkley and Cox, 2007). The naturalistic study design precluded clinical interviewing regarding perceived medication efficacy, emergent effects, or timing in relation to crashes, and thus informs protective effects of medication treatment rather than optimal dosing. Nevertheless, these analyses reflect the most extensive examination to date of the protective effects of medication treatment on prospective, objectively documented motor vehicle crashes.

3.2. Clinical and research implications

Results confirm that ADHD and Depression are significant risk factors for adverse driving outcomes (Wingen et al., 2006; Stavrinos et al., 2015), and indicate that this risk is greater than previously estimated – particularly for being involved in, and culpable for, crashes and near-crashes. Notably, this risk appears proportional to ADHD symptom severity, rather than an outcome of clinical status *per se*. Clinically, patient education regarding driving risk is warranted, particularly when considering medication changes. Psychostimulants and manual transmission vehicles may reduce but not eliminate risk for ADHD drivers

(Cox et al., 2011), and assessing daily driving routines (e.g., afternoon/evening vs. late night) has important implications for selecting among psychostimulant formulations (Merkel et al., 2016). Future studies are needed to identify specific, in-car behaviors that portend this risk, and determine why drivers with elevated but less severe ADHD symptoms – such as those with Depression – may have greater success executing evasive actions that avoid imminent crashes. Determining whether similar behaviors precede crashes between clinical groups and across ADHD severity levels will be helpful for developing transdiagnostic and disorder-specific interventions to reduce adverse driving outcomes (Vaa, 2003). In particular, the omnipresence of cellphones (O'Connor et al., 2017), social media access, and WiFi-connected vehicles may simultaneously provide both serious risk (e.g., distracted driving) and golden public health opportunity for intervention (e.g., real-time monitoring/intervention) (El Farouki et al., 2014; Jenkins et al., 2017; Reimer et al., 2010).

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jpsychires.2018.02.026.

References

Aduen, P.A., Kofler, M.J., Cox, D.J., et al., 2015. Motor vehicle driving in high incidence psychiatric disability: comparison of drivers with ADHD, depression, and no known psychopathology. J. Psychiatr. Res. 64, 59–66.

Antin, J., Lee, S., Hankey, J., et al., 2011. Design of the in-vehicle driving behavior and crash risk study. Transportation Research Board Accessible at. https://www.nap.edu/download/14494.

Antin, J., Stulce, K., Eichelberger, L., et al., 2015. Naturalistic driving study: descriptive comparison of the study sample with national data. Transportation Research Board Accessible at. https://www.nap.edu/download/22196.

Austin, M.P., Mitchell, P., Goodwin, G.M., 2001. Cognitive deficits in depression. Br. J. Psychiatry 178 (3), 200–206.

Barkley, R.A., 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, R.A., Murphy, K.R., O'Connell, T., et al., 2005. Effects of two doses of methylphenidate on simulator driving performance in adults with attention deficit hyperactivity disorder. J. Saf. Res. 36 (2), 121–131.

Barkley, R.A., Murphy, K.R., Fischer, M., 2010. ADHD in Adults: what the Science Says. Guilford Press.

Biederman, J., Fried, R., Monuteaux, M.C., et al., 2007. A laboratory driving simulation for assessment of driving behavior in adults with ADHD: a controlled study. Ann. Gen. Psychiatr. 6, 4.

Brunnauer, A., Laux, G., David, I., Fric, M., Hermisson, I., Möller, H.J., 2008. The impact of reboxetine and mirtazapine on driving simulator performance and psychomotor function in depressed patients. J. Clin. Psychiatr. 69 (12), 1880–1886.

Bulmash, E.L., Moller, H.J., Kayumov, L., Shen, J., Wang, X., Shapiro, C.M., 2006. Psychomotor disturbance in depression: assessment using a driving simulator paradigm. J. Affect. Disord. 93 (1), 213–218.

Centers for Disease Control and Prevention, 2016. National Center for Injury Prevention and Control. Web-based Injury Statistics Query and Reporting System (WISQARS) Fatal Injury Data. Accessed from. https://www.cdc.gov/injury/wisqars/overview/key_data.html 08/31/2017.

Chang, Z., Lichtenstein, P., D'Onofrio, B.M., et al., 2014. Serious transport accidents in adults with attention-deficit/hyperactivity disorder and the effect of medication: a population-based study. JAMA Psychiatry 71 (3), 319–325.

Chang, Z., Quinn, P.D., Hur, K., Gibbons, R.D., Sjölander, A., Larsson, H., D'Onofrio, B.M., 2017. Association between medication use for attention-deficit/hyperactivity disorder and risk of motor vehicle crashes. JAMA Psychiatry 74 (6), 597–603.

Cox, D.J., Madaan, V., Cox, B.S., 2011. Adult attention-deficit/hyperactivity disorder and driving: why and how to manage it. Curr. Psychiatr. Rep. 13 (5), 345–350.

Cox, D.J., Davis, M., Mikami, A.Y., Singh, H., Merkel, R.L., Burket, R., 2012. Long-acting methylphenidate reduces collision rates of young adult drivers with attention-deficit/hyperactivity disorder. J. Clin. Pharmacol. 32 (2), 225–230.

Di Milia, L., Smolensky, M.H., Costa, G., et al., 2011. Demographic factors, fatigue, and driving accidents: an examination of the published literature. Accid. Anal. Prev. 43 (2), 516–532.

Dorn, L., Matthews, G., 1995. Prediction of mood and risk appraisals from trait measures: two studies of simulated driving. Eur. J. Pers. 9, 25–42.

El Farouki, K., Lagarde, E., Orriols, L., et al., 2014. The increased risk of road crashes in

Attention Deficit Hyperactivity Disorder (ADHD) adult drivers: driven by distraction? Results from a responsibility case-control study. PLoS One 9 (12), 1–15.

Fuermaier, A.B., Tucha, L., Evans, B.L., et al., 2015. Driving and attention deficit hyperactivity disorder. J. Neural. Transm. 1–13.

Hankey, J., Perez, M.A., McClafferty, J., 2016. Description of the SHRP 2 naturalistic database and the crash, near-crash, and baseline data sets. Transportation Research Board Accessible at. https://www.nap.edu/download/22196.

Harman, J.S., Edlund, M.J., Fortney, J.C., 2015. Trends in antidepressant utilization from 2001 to 2004. Psychiatr. Serv. 611–616.

Hasin, D.S., Goodwin, R.D., Stinson, F.S., Grant, B.F., 2005. Epidemiology of major depressive disorder: results from the national epidemiologic survey on alcoholism and related conditions. Arch. Gen. Psychiatr. 62 (10), 1097–1106.

Hill, L.L., Lauzon, V.L., Winbrock, E.L., Li, G., Chihuri, S., Lee, K.C., 2017. Depression, antidepressants and driving safety. Inj Epidimiol 4, 10.

Jenkins, S., Codjoe, J., Alecsandru, C., Ishak, S., 2017. Exploration of the SHRP 2 NDS: Development of a Distracted Driving Prediction Model. Advances in Human Aspects of Transportation. Springer International Publishing, pp. 231–242.

Jerome, L., Habinski, L., Segal, A., 2006. Attention-deficit/hyperactivity disorder (ADHD) and driving risk: a review of the literature and a methodological critique. Curr. Psychiatr. Rep. 8 (5), 416–426.

Kessler, R.C., Bromet, E.J., 2013. The epidemiology of depression across cultures. Annu. Rev. Publ. Health 34, 119–138.

Kessler, R., Adler, L., Barkley, R., et al., 2006. The prevalence and correlates of adult ADHD in the United States: results from the national comorbidity survey replication. Am. J. Psychiatr. 163, 716–723.

Knouse, L.E., Bagwell, C.L., Barkley, R.A., et al., 2005. Accuracy of self-evaluation in adults with ADHD evidence from a driving study. J. Atten. Disord. 8 (4), 221–234.

Mannuzza, S., Klein, R.G., Bessler, A., et al., 1993. Adult outcome of hyperactive boys: educational achievement, occupational rank, and psychiatric status. Arch. Gen. Psychiatr. 50 (7), 565–576.

McCartt, A.T., Solomon, M.G., 2004. Tracking traffic citations through court adjudications to posting to public driver records. Traffic Inj. Prev. 5 (2), 93–100.

Merkel Jr., R.L., Nichols, J.Q., Fellers, J.C., Hidalgo, P., Martinez, L.A., Putziger, I., Burket, R.C., Cox, D.J., 2016 Mar. Comparison of on-road driving between young adults with and without ADHD. J. Atten. Disord. 20 (3), 260–269.

National Center for Statistics and Analysis, 2015. Annual Vehicle- Miles of Travel, 1980-2015 National Summary. Highway Statistics Series. National Highway Traffic Safety Administration, Washington, DC.

O'Connor, S.S., Shain, L.M., Whitehill, J.M., Ebel, B.E., 2017 Feb 28. Measuring a conceptual model of the relationship between compulsive cell phone use, in-vehicle cell phone use, and motor vehicle crash. Accid Anal Prev 99, 372–378.

Paelecke-Habermann, Y., Pohl, J., Leplow, B., 2005. Attention and executive functions in remitted major depression patients. J. Affect. Disord. 89 (1), 125–135.

Polanczyk, G., de Lima, M.S., Horta, B.L., et al., 2007. The worldwide prevalence of ADHD: a systematic review and metaregression analysis. Am. J. Psychiatr. 164 (6), 942–948.

Randell, N.J., Charlton, S.G., Starkey, N.J., 2016. Driving with ADHD performance effects and environment demand in traffic. J. Atten. Disord 1087054716658126.

Redelmeier, D.A., Chan, W.K., Lu, H., 2010. Road trauma in teenage male youth with childhood disruptive behavior disorders: a population based analysis. PLoS Med. 7 (11).

Reimer, B., Mehler, B., D'Ambrosio, L.A., et al., 2010. The impact of distractions on young adult drivers with attention deficit hyperactivity disorder (ADHD). Accid. Anal. Prev. 42 (3), 842.

Spijker, J., De Graaf, R., Bijl, R.V., et al., 2002. Duration of major depressive episodes in the general population: results from The Netherlands mental health survey and incidence study. Br. J. Psychiatry 181, 208–213.

Stavrinos, D., Garner, A.A., Franklin, C.A., et al., 2015. Distracted driving in teens with and without attention-deficit/hyperactivity disorder. Pediatr. Nurs. 30 (5).

Swensen, A., Birnbaum, H.G., Ben Hamadi, R., et al., 2004. Incidence and costs of accidents among attention-deficit/hyperactivity disorder patients. J. Adolesc. Health 35, 346.

Thames, A.D., Becker, B.W., Marcotte, T.D., et al., 2011. Depression, cognition, and self-appraisal of functional abilities in HIV: an examination of subjective appraisal versus objective performance. Clin. Neuropsychol. 25 (2), 224–243.

Vaa, T., 2003. Impairments, diseases, age and their relative risks of accident involvement: results from meta- analysis. In: Deliverable R1.1 of EU-project IMMORTAL. Institute of Transport Economics, Oslo TØI-Report 690.

Vaa, T., 2014. ADHD and relative risk of accidents in road traffic: a meta-analysis. Accid. Anal. Prev. 62, 415–425.

Valentine, J.C., Aloe, A.M., Lau, T.W., 2015. Life after NHST: how to describe your data without "p-ing" everywhere. Basic Appl. Soc. Psychol. 37 (5), 260–273.

Wåhlberg, A.E., Dorn, L., 2015. How reliable are self-report measures of mileage, violations and crashes? Saf. Sci. 76, 67–73.

Whitlock, G., Norton, R., Clark, T., Jackson, R., MacMahon, S., 2004. Motor vehicle driver injury and marital status: a cohort study with prospective and retrospective driver injuries. Inj. Prev. 10 (1), 33–36.

Wickens, C.M., Smart, R.G., Mann, R.E., 2014. The impact of depression on driver performance. Int. J. Ment. Health 12 (4), 524–537.

Wingen, M., Ramaekers, J.G., Schmitt, J.A., 2006. Driving impairment in depressed patients receiving long-term antidepressant treatment. J. Psychopharmacol. 188 (1), 84–91.