Association between decision-making under risk conditions and on-road driving safety among older drivers.

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Abstract

Objective: Despite theoretical models emphasising the likely importance of adaptive decision-making to maintaining safety on the roads, there has been a lack of research investigating this topic. This exploratory study aimed to determine if decision making under risk conditions, as measured by the Game of Dice Task, can explain additional variance in on-road driving safety beyond other well-validated predictors.

Method: Two hundred and thirty-nine cognitively normal Australian drivers aged 65-96 completed demographic and health questionnaires, vision testing, a neurocognitive test battery assessing cognitive flexibility, cognitive interference, episodic memory, verbal working memory, verbal fluency, and visuospatial function, the Game of Dice Task - a lab-based assessment of decision making under risk conditions, validated off-road driver screening measures and an on-road driving assessment along a standard route in urban traffic conditions administered by a trained Occupational Therapist.

Results: The number of risky choices made, but not the number of strategy changes, across trials of the Game of Dice Task independently predicted on-road safety ratings after controlling for visual acuity, cognitive test performance and off-road driver screening measures, B = -.146, 95% CI (-.276 to -.016).

Conclusion: Overall, this study offers the first evidence that decision-making is related to older adults' on-road driving safety, and makes recommendations for future research exploring the contribution of decision making to on-road safety.

Keywords: Decision-making, Older adults, Driver safety, Neuropsychological assessment, Risk assessment

Key Points

Question: This exploratory study investigated whether decision-making under objective risk conditions as measured by performance on a laboratory-based decision-making task can explain additional variance in older drivers' on-road safety beyond other well-validated predictors.

Findings: Scoring higher on risky decision-making independently predicted poorer on-road safety ratings after controlling for visual acuity, cognitive test performance and off-road driver screening measures.

Importance: This study provides the first empirical evidence that psychometrically assessed decision-making is independently associated with on-road driving safety among older drivers.

Next Steps: Future research should develop more ecologically valid assessments of driving-related decision making and continue to explore the potentially important contribution of decision-making to on-road driver safety.

Introduction

Motor vehicle crashes are the second largest cause of unintentional injury in older age (Australian Institute of Health and Welfare, 2019; DeGrauw et al., 2016). A number of studies have explored a broad range of cognitive factors that may contribute to impaired driving in older adults, including processing speed, memory, visuospatial skills and executive functions such as response inhibition and task switching (Anstey & Wood, 2011; Anstey et al., 2012; Matthias & Lucas, 2009; Wagner & Nef, 2011). However, research to date has not evaluated the association between performance on cognitive tests that involve decision-making and driving safety in older adults.

In day-to-day life, individuals are confronted with decisions that involve making judgements based on degrees of risk. The ability to make advantageous decisions – that is decisions that are unlikely to result in loss or harm - is an essential aspect of adaptive behavior. Theoretically, adaptive decision-making should be fundamental to maintaining safe driving. Michon's (1979; 1985) hierarchical model of driving skills and control suggests that active drivers regularly engage in decision-making, including pre-trip decisions regarding when to drive and when not to drive, and in-the-moment driving decisions such as choosing to maintain a safe distance from the vehicle ahead or reducing one's speed under potentially dangerous conditions (e.g. in wet weather). The latter form of on-road decision-making likely requires continuous assessment of risks within complex situations and making ineffective decisions at this stage would greatly increase risk of crashes (e.g. Farah et al., 2008). The Risk Homeostasis Theory (Fuller 2005; Taylor 1964; Wilde 1989) suggests that driver behavior is modified by the subjective appraisals of situational risks on-road. When judgement of risk is high, drivers adopt conservative driving behavior; when risk appraisals are low, riskier on-road behaviors are often observed (Fuller, 2011).

Decision-making under ambiguity and decision-making under risk

Laboratory-based assessments of decision-making can be distinguished into two classes depending on the degree to which they offer respondents explicit information regarding the possible future consequences of and probabilities for reward and punishment. On this basis, measures can be conceptualised as measuring either “decision-making under ambiguity” or “decision-making under risk” (Bechara et al., 2005, Brand et al., 2005b). In decision-making under ambiguity, individuals must choose between different options without explicit knowledge about the probability of particular outcomes, whereas in decision-making under risk, the future consequences of specific decisions as well as the probabilities for reward and punishment are explicitly outlined. In the most frequently used measure of decision-making under ambiguity, the Iowa Gambling Task (IGT) (e.g. Bechara et al., 1994, Bechara et al., 1999), individuals are required to select a card from one of four different decks (two advantageous, two disadvantageous) without knowledge of the probability of relative gains and losses associated with each deck. On the other hand, decision-making under risk has been frequently measured by the Game of Dice Task (GDT) (e.g. Brand et al., 2005b). In contrast to the IGT, the GDT requires individuals to decide between different alternatives that are explicitly related to a specific amount of gains and losses. In addition, winning probabilities are obvious from the beginning of the task. A study of experienced taxi drivers in Hong Kong found that those who had a documented history of traffic offences were more likely to make risky decisions on the IGT – where the consequences of decisions are ambiguous - than drivers who did not have a history of traffic offenses (Cheng, et al., 2016). Young male drivers who self-reported riskier on-road driving behavior demonstrated greater likelihood of risky choices on the IGT and another measure of risk taking behavior under ambiguous conditions, the Balloon Analog Risk Task (Ba et al., 2016). EEG data from the same drivers indicated that compared to safe drivers, risky drivers showed lower amplitudes of feed-back related negativity in the Anterior Cingulate Cortex, which has been shown to be important for rational cognition and risk-aversion (e.g. Carlson, et al., 2009). No study to date has assessed the relationship between decision making under risk and driving safety.

Alongside well-documented cognitive and socioemotional shifts in older age, there is growing evidence that decision-making processes are impacted by aging (Lim & Yu, 2015; Tymula et al., 2013). However, the degree and direction of the association between age and decision-making remains unclear (Bruine de Bruin et al., 2012; Hanoch et al., 2007; Peters et al., 2007). Older age has been associated with advantageous decision-making tendencies such as avoidance of sunk cost bias (i.e. the tendency to continue investments with poor return) (Bruine de Bruin et al., 2007; Strough et al., 2008), as well as negative effects including inconsistent application of decision rules (Bruine de Bruin et al., 2007), worse decision-making when potential options are increased (Besedes et al., 2012a) and susceptibility to framing effects (Bruine de Bruin et al., 2007; Finucane et al., 2005). Preliminary research exploring the association between age and decision-making under risk conditions using the Game of Dice Task found that older age was associated with less advantageous decision-making compared to younger age. However, the association between age and decision-making performance was moderated by executive function and logical thinking (Brand & Schiebener, 2013).

Despite interest in the effect of aging on risky decision making, its role in older driver safety has yet to be considered. Previous literature has demonstrated that older driver on-road safety is consistently associated with vision and specific cognitive factors (e.g., executive function, processing speed, visual attention, task switching, and spatial abilities; see Anstey et al., 2012), and several off-road tests (e.g., Useful Field of View, Hazard Perception Test, Multi-D Battery) have been developed and validated against on-road safety for use as screening measures for identifying at-risk drivers (e.g. Anstey et al., 2020). However, none of this previous work has included decision-making as a predictor measure, so it is unknown whether this aspect of cognition explains on-road safety over and above known predictors. If preliminary evidence for a relationship between decision making performance under risk conditions and driving safety is found, this would open new avenues for future research that aims to improve the accuracy of screening tools to identify unsafe older drivers.

Study aims

In this exploratory study, we aimed to determine if decision-making under risk, a form of cognition that is important to driving behaviour, explains unique variance in older drivers' on-road safety. Specifically, we examined whether the number of risky choices or the number of strategy changes made across trials of the Game of Dice Task (a laboratory-assessed decision-making task), explained unique predictive variance in occupational therapist ratings of older drivers' safety during an on-road test, after adjusting for visual acuity, cognitive measures and validated off-road driver screening measures. We hypothesised that poorer on-road driving safety would be associated with a higher number of risky choices on the Game of Dice task.

Materials and Methods

Study Population

The Driving Aging Safety and Health (DASH) project was undertaken in the Australian cities of Canberra and Brisbane. The current paper includes only the data from the Canberra sub-sample, who were administered the decision-making task. Community dwelling older drivers aged 65 years and over with a current valid driver's license were recruited through advertisements in newspapers, community groups, and General Practice and Health clinics between 2013 and 2016. Older drivers were also recruited into the sample from the ACT Health Disability and Rehabilitation Service (DARS), which assesses drivers who are medically fit to drive but referred due to concerns about driving safety, often in relation to cognitive impairment. A total of 327 older adults were recruited at the Canberra site. For the purpose of this analysis, we excluded participants who did not have data from the on-road test (*n* = 20). Of these 307 cases who completed the on-road driving test, we excluded those with self-reported dementia diagnoses (*n* = 4), insufficient data to establish cognitive impairment (*n* = 1) and those with MCI. (*n* = 54). Classification of MCI was conducted according to International Working Group criteria (Winblad et al., 2004), using validated measures of subjective cognitive decline, cognitive impairment (adjusted for age, gender and years of education), and instrumental activities of daily living. More information regarding the classification procedure is included in the Supplementary Materials. This study reports on a sample of *n* = 242 who met the criteria of being cognitively normal. Sample demographic and cognitive characteristics are presented in Table 1.

Table 1.
Sample demographics and cognitive characteristics (n=242)

	Mean	SD	Range
Demographics			
Age (years)	75.51	6.15	65 - 96
Gender (Females n,%)	98	41%	
Education (years)	15.77	3.93	6 – 31
Driving experience (years)	56.15	7.04	34 – 79
Self-reported driving distance (km/wk)	251.06	337.39	0 – 3712
Self-rated Physical health score	41.56	9.39	19.89 – 62.18
Self-rated Mental health score	56.19	7.76	32.40 – 70.13
Cognition			
MMSE score	28.93	1.13	26 – 30
Word list CVLT Trial 1 recall	6.24	1.96	1 – 12
Word list CVLT Trial 2 recall	9.06	2.58	3 – 15
Word list CVLT Trial 3 recall	10.49	2.69	3 – 16
Word list CVLT Delayed recall	9.34	3.13	1 – 16
Boston Naming Test total	28.69	1.84	21 – 30

Letter fluency (COWAT) total	43.57	11.50	10 – 91
BVRT Visual Copy total	9.50	0.83	4 – 10
Trail Making Test part B time (secs)	108.17	50.44	35 – 300
Digit Span backward	4.46	1.11	2 – 8
Stroop color-words (secs)	33.81	14.05	15 – 186
Game of Dice task no. of safe choices	12.23	5.73	0 – 18
Game of Dice task no. strategy changes	3.51	3.38	0 – 13

MMSE = Mini-Mental Status Exam, CVLT = California Verbal Learning Test (modified), COWAT = Controlled Oral Word Association Test BVRT = Benton Visual Retention Test.

Standard Protocol Approvals and Consents

The protocol was approved by the Human Research Ethics Committees (HREC) of ANU (2012/643) and ACT Government Health Directorate (ETH.2.13.028). Informed written consent was obtained.

Procedure and Measures

Participants attended the Centre for Research on Aging, Health and Wellbeing at the Australian National University for a comprehensive neuropsychological, sensorimotor and off-road driver skill assessment. Assessments took 1-2 hours with regular refreshment breaks to minimise fatigue. Tests included paper and pen, as well as computer-based tasks, and were administered by trained research assistants. Computer tasks required minimal computer literacy, with supervised practice trials provided to ensure full comprehension of task requirements prior to test trials. Questionnaires on driving habits, medical conditions, falls, and instrumental activities of daily living (IADLs) were self-completed prior to the off-road assessment. . The off-road assessment session was conducted prior to the participant undertaking an On-Road Test (ORT). A standardised research ORT was administered by a driver trained Occupational Therapist (OT) and qualified Driving Instructor (DI) who were masked to the results of the off-road driver screening assessments.

On-Road Driving Test

Participants completed a 50-minute ORT in an automatic vehicle with dual brake controls fitted, which followed a standard, validated protocol and scoring procedure that has been described previously (Anstey et al., 2018; Anstey et al., 2020; Eramudugolla et al., 2020; Wood, et al., 2008; 2009). Briefly, the route was pre-determined and incorporated situations that drivers typically encounter during suburban driving. The driving instructor provided turn by turn navigation instructions for 80% of the driving route. The remaining 20% of the drive was completed through self-navigation by the participants who were instructed to drive to a pre-determined destination. Seated in the rear passenger seat, the occupational therapist (OT) scored the participants' driving performance in the areas of general observation (scanning and attention), blind spot checks, lane positioning, braking/acceleration (maintaining a safe speed and braking), gap selection (gap selected when entering traffic or the gap between the driver and other vehicles) and approach to hazards (appropriate planning and preparation) (Mallon & Wood, 2004). Indication/signalling (appropriate use of directional indicator) were also assessed where appropriate. Drivers' overall on-road safety was rated by the OT on a scale of 1 to 10, with higher scores indicating better driver safety. Specific driving errors were calculated as the % of errors as a function of opportunity for each error type during the driver instructed component of the on-road test. Additionally, errors were classified as 'critical errors' if they contravened road laws (e.g., not stopping at a stop sign), obstructed traffic, or required instructor intervention to prevent a crash.

Binocular Visual Acuity

Static high contrast visual acuity was assessed with a LogMAR Australian Vision Chart 5. Visual acuity was selected as it comprises one of the key vision measures in the standards for fitness to drive. Participants were seated 3.8 meters from the chart and wore corrective lenses used for driving. One eye was covered at a time, with participants required to read the letters from right to left when viewing with the left eye, and left to right when viewing with the right eye. The binocular visual acuity score represented how many letters/lines participants could read, where each letter correct was scored as -0.02 logMAR units with more negative scores indicating better performance.

Cognitive Tests

The *Trail Making Test Part B (*Reitan, 1985) was used to measure cognitive flexibility. The time to complete Part B of the task was used, instead of the residual or difference score from Part A, as this measure has been found to have greater predictive value for Game of Dice Task performance (Schiebener et al., 2014). Time to complete the *Stroop Color Word Association Test* (Spreen et al., 1998) (Stroop C) was taken as a measure of cognitive interference. Episodic memory was measured using the *California Verbal Learning Test* (CVLT; Delis et al., 1987). The administration of the CVLT was modified for the present study such that three trials of the CVLT were administered (rather than the usual five trials), followed by a 20-minute delayed recall. This modification was made to minimise testing time and participant burden. Performance on the delayed recall trial of the CVLT was used as a measure of episodic memory in this study. Verbal working memory was assessed by the *Digits Span Backwards* task from the Wechsler Memory Scale (Wechsler, 1945). Verbal fluency was measured by the *Controlled Oral Word Association Test* (COWAT; Benton, Hamshur & Sivan, 1983). Visuospatial function was assessed using the copying task from the *Benton Visual Retention Test* (Administration C) (BVRT; Benton, 1963).

Off-Road Screening Tests for Driving Safety

The three off-road driver screening tests included in the present analyses have been found to be strongly predictive of safe/unsafe drivers in previous research (Anstey et al., 2020; Myers et al., 2020; Owsley, et al., 1998). The *Useful Field of View*® (UFOV) (Subtest 2) is a computer-based test of visual processing speed and divided attention, with high reliability and validity demonstrated in other large studies to predict crash risk in older drivers (Anstey et al., 2017, 2018; Edwards et al., 2005). Participants were instructed to attend to two targets presented simultaneously on screen: a central schematic image of a car or truck with a second car figure presented randomly at one of eight peripheral locations. Performance is scored as the minimum target exposure at which the participant can correctly identify both the central target as well as the location of the peripheral target 75% of the time. The *Hazard Perception Test* (HPT: McKenna & Crick, 1994; Whetton, Hill & Horswill, 2011) is a computer-based test used to assess the ability to identify and respond to dangerous situations on the road ahead. The HPT involves a series of 20 short real-world driving video clips featuring a moving car, presented from the driver's point of view. Participants were asked to tap the touch-sensitive computer monitor as early as possible to indicate the location of road users who were likely to be involved in traffic conflicts with the camera car. Higher mean response time across all trials indicates poorer hazard perception. The *Multi-D* is a computer-based test designed to assess multi-domain driver safety (Anstey et al., 2012; Wood et al., 2008). The Multi-D includes three subtests – choice colour reaction time (requiring hand and foot responses and inhibition of responses), sensitivity to central visual motion (using random dot stimuli presented at 3.2m), and balance or postural sway (using a sway meter to measure body displacement at the level of the waist). The Multi-D battery has been shown to be the most effective classifier of safe/unsafe older drivers based on OT-rated driver safety scores (Anstey et al., 2020; Wood et al., 2008; Wood et al. 2013).

Decision-making Under Risk Conditions

Decision-making under risk was assessed using the *Game of Dice Task* (GDT; Brand et al., 2005). The GDT is a computerised decision-making task, where participants are instructed to maximise their fictitious starting capital of $1000 within 18 throws of a single virtual die. Before each throw, participants have to guess which number will appear on the computer screen by selecting either a single number (e.g., 3) or combinations of two (e.g., 1

2), three (e.g., 1 2 3), and four numbers (e.g., 1 2 3 4). Each alternative is associated with a specific winning probability and a specific amount of gain/loss: Single number ($1000), two numbers ($500), three numbers ($200) and four numbers ($100), such that the value of monetary gain/loss associated with each option is inversely related to the probability of winning. For example, by selecting the alternative with a single number (e.g., by selecting 3), the participant has a probability of 1/6 to win $1000. The participant will win $1000 if the selected number is thrown; otherwise, the participant will lose $1000 – making this option high risk. Alternatives and associated gains/losses remain visible on the screen for the whole task duration. Before the task begins, participants are explicitly instructed about rules, amounts of gains/losses associated with each alternative, but not about which alternative is the most advantageous. After a choice is made, the computer indicates which number is thrown, whether the participant has won/lost, the residual capital, and the number of throws remaining. Gains and losses are also indicated by distinct acoustic signals. The GDT generates two primary outcomes: 1) the number of risky decisions made across the 18 trials (i.e., betting on 1 or 2 numbers), with higher scores indicating riskier decision-making under explicit risk conditions, and 2) the number of strategy changes, from safe (betting on 3 or 4 numbers) to unsafe (betting on 1 or 2 numbers) and vice versa, across trials, with higher scores indicating less consistent decision-making under risk conditions. The GDT has been used to study decision making capacity in life-course samples that include adults aged up to 80 years (e.g. Brand & Scheibener, 2013), as well as older adults living with Parkinson's Disease (Brand et al., 2005). The GDT has shown convergent validity with other neuropsychological assessments of decision-making such as the Wisconsin Card Sorting Task (Brand et al., 2005).

Statistical Approach

All statistical analyses were conducted using SPSS 25 (Chicago: SPSS Inc.).

Stage 1 (missing data approach): Missing data for visual acuity, cognitive measures, off-road driver screening tasks, and the Game of Dice Task were imputed using a fully conditional specification approach (Van Buuren et al., 2006) with 10 imputations in SPSS. Percentage of missing data for each variable is included in Supplementary Table 1.

Stage 2 (bivariate correlations for driver safety rating): Pearson's correlations were used to determine bivariate correlations between the decision-making measures, cognitive tests, off-road driver screening measures and driver safety rating. Only those variables that were significantly correlated with the overall driver safety (at $p < .05$) were included in subsequent regression analyses.

Stage 3 (Regression on on-road safety rating): Hierarchical linear regression models with z-transformed standardised variables were used to evaluate the predictive contribution of decision-making to OT-rated driver safety. Variables that were significantly correlated with on-road safety in Stage 2 were entered as covariates in Models 1 – 3. Visual acuity was added in Model 1 as it is the primary prerequisite for determining driver safety in the real-world and is arguably a prerequisite for performance on other measures included in this study. Cognitive tests other than GDT were added in Model 2, followed by more ecologically-valid off-road driver safety screening tasks in Model 3. Finally, decision-making was added in Model 4 to examine the unique predictive variance of decision-making to on-road driver safety ratings after adjusting for all variables entered in preceding models.

Results

Bivariate Correlations Between OT-Rated Driver Safety Rating, Visual Acuity, Cognition, Off-Road Driver Screening Tests and Decision-making Performance on the GDT

Bivariate correlations between variables using pooled imputed data are displayed in Supplementary Table 2. Significant correlations were confirmed between driver safety rating and the following measures: Multi-D (r = -0.40, p < .001), HPT (r = -0.38, p < .001), UFOV (r = -0.33, p < .001), Trails B (r = -0.33, p < .001), CVLT delayed recall (r = 0.27, p < .001), GDT risky choices (r = -0.24, p < .001), binocular visual acuity (r = -0.23, p < .001), Stroop C (r = -0.23, < .001) and GDT strategy changes (r = -0.19, p = .007). Digit Span Backward, BVRT and COWAT were not significantly correlated with OT-rated driver safety among the present sample and were excluded from further regression analyses predicting OT-rated driver safety rating.

Decision-making Under Explicit Risk as a Predictor of OT-Rated Driver Safety Rating

Model summary statistics for hierarchical regression analyses of standardised predictors of OT-rated driver safety using original data and 10 imputed data sets are reported separately in Supplementary Table 3. Model 1 explained approximately 4.5% of variance in driver safety rating (adj R^2 range: 0.042 to 0.049 for the 10 imputed datasets), Model 2 accounted for 11.8% (adj R^2 range: 0.111 to 0.126), Model 3 accounted for 23% (adj R^2 range: 0.201 to 0.253) and Model 4 accounted for 25% (adj R^2 range: 0.223 to 0.273). The R^2 change was significant for each successive model, with the addition of GDT in Model 4 accounting for an additional 2.6% of variance in driver safety rating over and above Model 3 variables (R^2 change range: 0.023 to 0.030).

Hierarchical regression coefficients predicting OT-rated driver safety among older adult drivers are displayed in Table 2. Using pooled imputed data, the number of risky decision made on the GDT was a significant unique predictor of driver safety rating after controlling for visual acuity, cognitive test performance and performance on off-road driver screening measures, B = -.146, 95% CI (-.276 to -.016), p = .028. Number of strategy changes on the

GDT was not a unique predictor of driver safety rating after controlling for covariates, $B = -.050$, 95% CI (-.188 to .087), $p = .471$.

Table 2.
Hierarchical regression coefficients predicting OT-rated driver safety among cognitively normal older adult drivers using pooled imputed data.

Model	Variables entered into model	Unstandardized Coefficients		Standardized B	T	P	95% CI		Fraction Missing Info.	Relative Increase Variance	Relative Efficiency
		B	Std. Error				Lower Bound	Upper Bound			
1	Visual Acuity	-0.225	0.068	-0.225	-3.296	0.001	-0.358	-0.091	0.006	0.006	0.999
2	Visual Acuity	-0.132	0.069	-0.133	-1.912	0.056	-0.267	0.003	0.013	0.013	0.999
	TMT-B (time)	-0.228	0.090	-0.254	-2.544	0.011	-0.404	-0.052	0.043	0.045	0.996
	Stroop C	-0.033	0.090	-0.007	-0.363	0.717	-0.210	0.145	0.088	0.095	0.991
	CVLT Delayed Recall	0.134	0.077	0.116	1.746	0.081	-0.016	0.285	0.038	0.039	0.996
	Digit-Back	-0.013	0.070	-0.013	-0.183	0.855	-0.150	0.124	0.023	0.023	0.998
	BVRT	-0.022	0.075	-0.008	-0.299	0.765	-0.169	0.124	0.068	0.072	0.993
3	Visual Acuity	-0.060	0.067	-0.061	-0.892	0.372	-0.192	0.072	0.030	0.031	0.997
	TMT-B (time)	-0.092	0.090	-0.105	-1.023	0.306	-0.270	0.085	0.064	0.068	0.994
	Stroop C	0.053	0.087	0.069	0.615	0.539	-0.117	0.223	0.082	0.088	0.992
	CVLT Delayed Recall	0.100	0.074	0.094	1.360	0.174	-0.044	0.245	0.041	0.042	0.996
	Digit-Back	-0.056	0.068	-0.065	-0.827	0.408	-0.190	0.077	0.027	0.027	0.997
	BVRT	-0.066	0.072	-0.034	-0.913	0.362	-0.208	0.076	0.091	0.099	0.991
	Multi-D	-0.191	0.099	-0.164	-1.933	0.055	-0.386	0.005	0.280	0.366	0.973
	HPT (time)	-0.243	0.074	-0.243	-3.290	0.001	-0.387	-0.098	0.143	0.162	0.986
	UFOV	-0.137	0.083	-0.165	-1.648	0.100	-0.300	0.026	0.116	0.128	0.989
4	Visual Acuity	-0.052	0.066	-0.055	-0.779	0.436	-0.182	0.078	0.031	0.031	0.997
	TMT-B (time)	-0.114	0.090	-0.127	-1.274	0.203	-0.290	0.062	0.059	0.062	0.994
	Stroop C	0.048	0.086	0.063	0.563	0.573	-0.120	0.216	0.080	0.085	0.992
	CVLT Delayed Recall	0.083	0.074	0.076	1.121	0.262	-0.062	0.227	0.036	0.037	0.996
	Digit-Back	-0.047	0.068	-0.055	-0.692	0.489	-0.180	0.086	0.028	0.029	0.997

BVRT	-0.084	0.072	-0.048	-1.163	0.245	-0.225	0.057	0.089	0.096	0.991
Multi-D	-0.159	0.100	-0.130	-1.590	0.115	-0.357	0.039	0.301	0.405	0.971
HPT (time)	-0.245	0.074	-0.243	-3.319	0.001	-0.390	-0.100	0.153	0.175	0.985
UFOV	-0.118	0.082	-0.147	-1.438	0.151	-0.278	0.043	0.100	0.109	0.990
GDT Frequency of Risky Choices	-0.146	0.066	-0.137	-2.197	0.028	-0.276	-0.016	0.021	0.021	0.998
GDT Frequency of Strategy Changes	-0.050	0.070	-0.056	-0.722	0.471	-0.188	0.087	0.096	0.104	0.990

Note. Dependent Variable: OT-Rated Driver Safety (continuous). Z scores of all predictor variables used in analyses. TMT-B = Trail Making Test – Part B, Stroop C = Stroop Color Word Association Test, CVLT = California Verbal Learning Test, BVRT = Benton Visual Retention Test, HPT = Hazard Perception Test, UFOV = Useful Field of View Task, GDT = Game of Dice Task.

Discussion

This exploratory study found that a higher number of both risky choices and strategy changes across trials of the Game of Dice Task was associated with poorer driver safety ratings in bivariate analyses. Regression analyses revealed that number of risky choices, but not number of strategy changes, contributed to the prediction of overall driver safety rating after controlling for the influence of binocular visual acuity, cognitive flexibility measured by TMT-B response time, verbal response inhibition as measured by Stroop C response time, episodic memory measured by CVLT delayed recall, and performance on three off-road driver safety assessments – the Multi-D, Useful Field of View and Hazard Perception Tests. One SD increase in risky choices predicted an average decrease of 0.14 points on the driver safety score.

In providing the first evidence for the relationship between decision-making under risk conditions and objectively-assessed on-road driver safety, the results extend previous research that has demonstrated a relationship between performance on laboratory assessments of decision-making under ambiguous conditions and self-reported risky driving among young adults (e.g. Ba et al., 2016; Cheng, Ng, & Lee, 2012) and taxi drivers (Cheng, Ting, Lui & Ba, 2016). While more research is needed to support the present results, the identification of decision-making capacity as a likely new contributor to on-road driving safety offers a potential new target for interventions designed to improve driving safety among older cohorts.

In the context of Michon's (1979; 1985) hierarchical model of driving skills and control, the present results suggest that decision-making is involved in maintaining safe driving behavior, and suggests that assessments that measure decision-making under risk may be tapping into an important form of cognition that has yet to be considered in assessments of older adult driver safety. It may be the case that older drivers in the present sample who made riskier choices on the GDT and were also more unsafe during the on-road test, may be perceiving risks differently to their safer counterparts. For example, the Risk Homeostasis Theory (Fuller 2005; Taylor 1964; Wilde 1989) suggests that driver behavior is modified by the subjective appraisals of situational risks on-road, with lower risk appraisals associated with riskier on-road behaviors (Fuller, 2011). Relatedly, it is also possible that the relationship between decision-making under objective risk and driver safety is explained in part by differences in participants' default mode of information processing (Kahneman, 2003). Brand et al. (2008) found that participants who performed more advantageously on the GDT were able to reason more accurately and were more likely to prefer an analytical-rational mode of information processing and inhibit more intuitive information processing. We speculate that less risky decision making performance in the present study may indicate better ability to weight the risks associated with a particular choice. Older drivers who misjudge risks may be more likely to engage in risky driving behavior, particularly in the case of on-road behaviors that rely on processing of complex information.

Limitations and Future Directions

The strongest predictors of on-road safety rating in the final model were performance on the Hazard Perception Test, and number of risky choices on the Game of Dice Task. At face value, this may seem to conflict with previous work that has used the Driving, Ageing and Health Study data to demonstrate that the Multi-D is the strongest single predictor of older driver safety (e.g. Anstey et al., 2020). However, unlike previous work, the present study restricted the sample to only those older drivers who were not cognitively impaired in order to isolate the effect of decision making in the context of normal cognitive ageing. In addition, we note that the main outcome variable – driver safety rating – was treated differently in the present study compared to previous work. In this paper, we chose to retain the outcome in the original continuous form, whereas previous work has re-coded the driver safety rating into a dichotomous safe/unsafe variable, in line with their study aims to most accurately categorise safe and unsafe drivers.

The Game of Dice Task, like the majority of other laboratory-based assessments of decision-making, uses financial gambling scenarios to measure decision-making behavior and so lacks ecological validity for traffic scenarios faced by older drivers. Despite this, the task appears to be tapping into executive issues that are related to driving performance that are not captured by other cognitive measures. The development of new tasks that measure decision making using scenarios that are directly related to on-road driving behaviour would enable more robust research exploring the newly documented relationship between decision making under risk and on-road safety among older drivers.

Other methodological limitations of this study include our use of non-random sampling, unequal gender representation, higher education than the population, and healthy volunteer bias as explained in another recent paper using the complete DASH dataset (Anstey et al., 2020), although, similar bias has been reported using samples generated from the electoral roll and all driving assessment studies have the same bias (Wood et al., 2008). The decision making measure used in the present study also suffered from a high percentage of missing data, which may have been due to failure to complete all 18 trials of the computerised task among the present sample, resistance to the completion of a gambling task on the basis of ideological grounds, or other factors (e.g., motor difficulties, fatigue). While a fully conditional specification approach was used to estimate missing data in the most appropriate way, we acknowledge that future research should develop more ecologically-valid measures of decision making that are also less susceptible to missing data.

Future studies that include assessment of age-related changes in neural and psychological factors that contribute to decision-making (see Samanez-Larkin & Knutson, 2015 for a review), would also help to clarify the mechanisms by which decision-making may be impacting older driver safety. Studies that do so would also enable testing of the extent to which relationships demonstrated in a laboratory-based setting translate to real-world behavior.

Conclusions

This exploratory study is the first to demonstrate that cognitive abilities involved in decision-making under risk conditions may influence driving safety in older adults. This warrants further investigation with a wider range of tests and may inform the development of expanded assessments designed to measure older driver safety.

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Description of MCI Screening Procedure

Classification of MCI was conducted according to International Working Group criteria (Winblad et al., 2004), using validated measures of subjective cognitive decline, cognitive impairment (adjusted for age, gender and years of education), and instrumental activities of daily living.

Specifically, participants had to a) meet criteria for absence of dementia – defined as MMSE>24 and/or no reported diagnosis; b) subjectively report cognitive decline defined as MAC-Q score>24 (Crook et al., 1992); c) have objective cognitive impairment on one or more of 5 neurocognitive domains assessed by standardised tests and defined as more than 1 standard deviation below the age, gender and education stratified published norms (i.e., z-score< – 1.0) in any of the cognitive domains assessed (Complex Attention, Learning and Memory, Language, Visuospatial skills, and Executive Function); and d) have minimal impairments in instrumental activities of daily living operationalized as no difficulties attributed to cognition on the Health and Retirement Survey IADL items (Juster & Suzman, 1995).

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Supplementary Table 1.
Description of complete and missing data (N = 327).

	Cases with Complete Data	Cases with Missing Data	% Missing Data
GDT Strategy Changes	272	55	20.22
GDT Risky Choices	272	55	20.22
Visual Acuity	324	3	0.93
TMT-B (time)	314	13	4.14
Stroop C	314	13	4.14
CVLT Delayed Recall	313	14	4.47
Digit Back	314	13	4.14
BVRT	313	13	4.15
COWAT	314	13	4.14
UFOV	305	22	7.21
HPT	305	22	7.21
Multi-D	281	46	16.37
On-Road Test	242	17	7.02

GDT = Game of Dice Task, TMT-B = Trail Making Test – Part B, Stroop C = Stroop Color Word Association Test, CVLT = California Verbal Learning Test, BVRT = Benton Visual Retention Test, COWAT = Controlled Oral Word Association Test, UFOV = Useful Field of View Task, HPT = Hazard Perception Test.

Supplementary Table 2.

Bivariate Correlations between OT-rated driver safety rating, visual acuity, cognition, off-road driver screening tests and decision making under objective risk conditions.

	OT Safety Rating	Visual Acuity	Trails B (time)	Stroop C	CVLT Delayed Recall	Digit Span Backward	BVRT	COWAT	UFOV	HPT (time)	Multi-D	GDT Frequency of Safe Choices	GDT Strategy Changes
OT Safety Rating	1	-.225**	-.330**	-.200**	.247**	0.093	0.085	-0.012	-.335**	-.381**	-.381**	.231**	-.174*
Visual Acuity		1	.247**	.134*	-.264**	-0.095	-0.122	-.162*	.267**	.169**	.289**	-0.117	0.079
Trails B (time)			1	.542**	-.386**	-.265**	-.205**	-.354**	.417**	.309**	.556**	-0.069	0.026
Stroop C				1	-.374**	-.237**	-.360**	-.345**	.393**	.221**	.472**	-0.068	0.123
CVLT Delayed Recall					1	.224**	.210**	.233**	-.367**	-0.097	-.365**	0.127	-.213**
Digit Span Backward						1	.137*	.372**	-.371**	-0.116	-.213**	0.000	-0.068
BVRT							1	.127*	-.282**	-0.030	-.304**	.169*	-0.065
COWAT								1	-.280**	-.194**	-.392**	-0.011	-0.056
UFOV									1	.278**	.413**	-.172*	0.113
HPT (time)										1	.390**	-0.041	0.124
Multi-D											1	-.217**	.148*
GDT Frequency of Safe Choices												1	-.318**

Note. * Correlation is significant at the .05 level (2-tailed), ** Correlation is significant at the .01 level (2-tailed). Data based on pooled estimates from 10 imputations. TMT-B = Trail Making Test – Part B, Stroop C = Stroop Color Word Association Test, CVLT = California Verbal Learning Test, BVRT = Benton Visual Retention Test, COWAT = Controlled Oral Word Association Test, UFOV = Useful Field of View Task, HPT = Hazard Perception Test, GDT = Game of Dice Task.

Supplementary Table 3.
Model summary statistics using the original data and ten imputed datasets.

Imputation Number	Model	R	R Square	Adjusted R Square	SE of the Estimate	Change Statistics					ANOVA Statistics				
						R Square Change	F Change	df1	df2	Sig. F Change	Sum of Squares	df	Mean Square	F	Sig.
Original data	1	0.225	0.051	0.046	0.979	0.051	9.957	1	186	0.002	9.538	1	9.538	9.957	.002
	2	0.377	0.142	0.114	0.943	0.091	3.857	5	181	0.002	26.695	6	4.449	5.002	.000
	3	0.510	0.260	0.222	0.883	0.118	9.428	3	178	0.000	48.771	9	5.419	6.943	.000
	4	0.533	0.284	0.239	0.874	0.024	2.971	2	176	0.054	53.308	11	4.846	6.347	.000
1	1	0.231	0.053	0.049	0.977	0.053	11.637	1	206	0.001	11.109	1	11.109	11.637	.001
	2	0.379	0.143	0.118	0.941	0.090	4.215	5	201	0.001	29.772	6	4.962	5.603	.000
	3	0.486	0.236	0.201	0.895	0.093	8.029	3	198	0.000	49.078	9	5.453	6.804	.000
	4	0.514	0.264	0.223	0.883	0.028	3.736	2	196	0.026	54.906	11	4.991	6.400	.000
2	1	0.228	0.052	0.047	0.978	0.052	11.200	1	205	0.001	10.712	1	10.712	11.200	.001
	2	0.380	0.145	0.119	0.940	0.093	4.347	5	200	0.001	29.928	6	4.988	5.641	.000
	3	0.515	0.265	0.231	0.878	0.120	10.733	3	197	0.000	54.772	9	6.086	7.888	.000
	4	0.541	0.292	0.252	0.866	0.027	3.788	2	195	0.024	60.456	11	5.496	7.325	.000
3	1	0.217	0.047	0.042	0.980	0.047	10.093	1	205	0.002	9.703	1	9.703	10.093	.002
	2	0.383	0.147	0.121	0.939	0.100	4.695	5	200	0.000	30.405	6	5.068	5.747	.000
	3	0.507	0.257	0.223	0.883	0.110	9.715	3	197	0.000	53.134	9	5.904	7.570	.000
	4	0.531	0.282	0.242	0.872	0.025	3.446	2	195	0.034	58.379	11	5.307	6.974	.000
4	1	0.216	0.047	0.042	0.980	0.047	10.080	1	205	0.002	9.690	1	9.690	10.080	.002
	2	0.386	0.149	0.123	0.938	0.102	4.783	5	200	0.000	30.739	6	5.123	5.821	.000
	3	0.515	0.265	0.232	0.878	0.117	10.428	3	197	0.000	54.863	9	6.096	7.905	.000
	4	0.539	0.290	0.250	0.867	0.025	3.451	2	195	0.034	60.055	11	5.460	7.256	.000
5	1	0.226	0.051	0.046	0.978	0.051	11.050	1	206	0.001	10.578	1	10.578	11.050	.001
	2	0.386	0.149	0.124	0.938	0.098	4.648	5	201	0.000	31.016	6	5.169	5.878	.000
	3	0.507	0.257	0.224	0.883	0.108	9.608	3	198	0.000	53.479	9	5.942	7.625	.000
	4	0.536	0.288	0.248	0.869	0.030	4.176	2	196	0.017	59.785	11	5.435	7.198	.000
6	1	0.228	0.052	0.047	0.978	0.052	11.245	1	206	0.001	10.755	1	10.755	11.245	.001

	2	0.380	0.145	0.119	0.940	0.093	4.366	5	201	0.001	30.057	6	5.010	5.666	.000
	3	0.503	0.253	0.219	0.885	0.109	9.610	3	198	0.000	52.645	9	5.849	7.466	.000
	4	0.525	0.276	0.235	0.876	0.023	3.070	2	196	0.049	57.358	11	5.214	6.795	.000
7	1	0.225	0.051	0.046	0.979	0.051	10.929	1	205	0.001	10.465	1	10.465	10.929	.001
	2	0.386	0.149	0.123	0.938	0.098	4.605	5	200	0.001	30.730	6	5.122	5.819	.000
	3	0.534	0.285	0.253	0.866	0.137	12.575	3	197	0.000	59.024	9	6.558	8.745	.000
	4	0.558	0.311	0.273	0.855	0.026	3.672	2	195	0.027	64.387	11	5.853	8.016	.000
8	1	0.223	0.050	0.045	0.979	0.050	10.695	1	205	0.001	10.252	1	10.252	10.695	.001
	2	0.389	0.152	0.126	0.937	0.102	4.811	5	200	0.000	31.350	6	5.225	5.957	.000
	3	0.526	0.277	0.244	0.871	0.125	11.361	3	197	0.000	57.224	9	6.358	8.376	.000
	4	0.551	0.303	0.264	0.860	0.026	3.680	2	195	0.027	62.663	11	5.697	7.708	.000
9	1	0.225	0.051	0.046	0.979	0.051	11.094	1	208	0.001	10.623	1	10.623	11.094	.001
	2	0.369	0.136	0.111	0.945	0.086	4.028	5	203	0.002	28.599	6	4.766	5.340	.000
	3	0.505	0.255	0.221	0.884	0.118	10.594	3	200	0.000	53.442	9	5.938	7.596	.000
	4	0.531	0.282	0.242	0.872	0.027	3.772	2	198	0.025	59.181	11	5.380	7.073	.000
10	1	0.228	0.052	0.047	0.978	0.052	11.262	1	205	0.001	10.768	1	10.768	11.262	.001
	2	0.376	0.141	0.116	0.942	0.089	4.162	5	200	0.001	29.241	6	4.874	5.490	.000
	3	0.505	0.255	0.221	0.884	0.113	9.998	3	197	0.000	52.700	9	5.856	7.487	.000
	4	0.528	0.279	0.239	0.874	0.024	3.296	2	195	0.039	57.737	11	5.249	6.868	.000

Model 1 includes the constant and visual acuity. Model 2 includes Model 1 plus Trail Making Task B (time), Stroop C (time), and California Verbal Learning Task delayed recall performance. Model 3 includes Model 2 plus Hazard Perception Test (time), Useful Field of View Score, and Multi-D risk probability. Model 4 includes Model 3 plus Frequency of Risky Choices and Frequency of Strategy Changes on the Game of Dice Task.