The Role of Cognitive and Visual Abilities as Predictors in the Multifactorial Model of Driving Safety

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Abstract

Objective: The current study evaluated part of the Multifactorial Model of Driving Safety to elucidate the relative importance of cognitive function and a limited range of standard measures of visual function in relation to the Capacity to Drive Safely. Capacity to Drive Safely was operationalized using three validated screening measures for older drivers. These included an adaptation of the well validated Useful Field of View (UFOV) and two newer measures, namely a Hazard Perception Test (HPT), and a Hazard Change Detection Task (HCDT).

Method: Community dwelling drivers (n = 297) aged 65 to 96 were assessed using a battery of measures of cognitive and visual function.

Results: Factor analysis of these predictor variables yielded factors including Executive/Speed, Vision (measured by visual acuity and contrast sensitivity), Spatial, Visual Closure, and Working Memory. Cognitive and Vision factors explained 83 to 95% of age-related variance in the Capacity to Drive Safely. Spatial and Working Memory were associated with UFOV, HPT and HCDT, Executive/Speed was associated with UFOV and HCDT and Vision was associated with HPT.

Conclusion: The Capacity to Drive Safely declines with chronological age, and this decline is associated with age-related declines in several higher order cognitive abilities involving manipulation and storage of visuospatial information under speeded conditions. There are also age-independent effects of cognitive function and vision that determine driving safety.

Keywords: hazard perception, Useful Field of View, cognitive decline, driving

1 Introduction

Various brief screening instruments have been developed to assess the driving skills and predict the potential 'risk' of older drivers. The most widely validated and well researched of these screening instruments is the Useful Field of View® (Ball and Owsley 1993); however other instruments that measure change detection (Wetton *et al.* 2010), and hazard perception (Horswill *et al.* 2010a) have also been reported in the literature, as have test batteries that incorporate a range of sensorimotor measures (Ball *et al.* 2006, Wood *et al.* 2008).

Visual function and cognition are two key components of the Multifactorial Model of Driving Safety (Anstey *et al.* 2005b). In this model they are intercorrelated, and both predict the Capacity to Drive Safely. The Capacity to Drive Safely, in conjunction with other factors such as self-monitoring (Horswill *et al.* 2011) and beliefs about one's driving competence under varying conditions (Okonkwo *et al.* 2008), is argued to predict actual driving behavior. Off-road driver screening tests are measures of the Capacity to Drive Safely whereas 'on-road' driving measures assess actual 'driving behavior'. The present study focuses on elucidating the nature of the relationship between cognitive and visual abilities in relation to the Capacity to Drive Safely.

At present, several questions remain unanswered regarding the relative role of visual and cognitive function in predicting driving safety. Whilst visual testing is mandatory in many jurisdictions (Cole 2002), cognitive screening is not required (to our knowledge) despite evidence that both cognitive and visual function predict crashes and unsafe driving. A comparison of the relative importance of visual and cognitive function for predicting safe driving is therefore warranted and will contribute to an evaluation of whether the current approach of screening visual and not cognitive abilities, is appropriate.

Both executive function and processing speed have been proposed as the main cognitive abilities that impact on older drivers' performance (McKnight and McKnight 1999, Daigneault *et al.* 2002), yet it is important to evaluate their contribution in the context of other visual-cognitive abilities that show age-related declines.

Age-related changes in visual function, particularly reductions in visual acuity (Burg 1967, 1968, Higgins and Wood 2005, Owens *et al.* 2007) and visual field loss (Johnson and Keltner 1983, Wood *et al.* 2009b) have been associated with crash risk in older adults. However, research has shown that visual tests alone are a poor predictor of driving performance (Johnson and Keltner 1983, Haymes *et al.* 2007, Wood *et al.* 2009b). Eye disease is also associated with an increased risk of unsafe driving (Owsley *et al.* 1998b, Haymes *et al.* 2007).

Understanding how cognitive and visual ageing affect performance on instruments designed to predict driving skills in late life will not only assist in improving the design of these measures, but will also indicate whether specific screening instruments are more suitable for different sub-populations, in the same way that a neuropsychological test battery would be designed differently for different populations. Moreover, accurate theoretical models of the interrelationships between sensory and cognitive function are required for the development of effective interventions to improve driving safety, such as tailored cognitive training programs (Jobe *et al.* 2001, Roenker *et al.* 2003, Edwards *et al.* 2006), and effective management and treatment of eye disease. Such training studies have been undertaken with driver screening instruments as the outcome measure because they are safer, cheaper, and potentially more reliable and valid (e.g. extreme crash situations can be presented at a high frequency and in a more standardized manner) than on-road driving tests (Horswill *et al.* 2010b).

The present study operationalizes the 'capacity to drive safely' via inclusion of three validated screening measures that have been linked to self-reported crashes or unsafe on-road driving performance. These are an adaptation of the Useful Field of View® (UFOV), a Hazard Perception Test (HPT) and a Hazard Change Detection Test (HCDT). The UFOV has been found to be a strong predictor of crashes in both retrospective (Owsley *et al.* 1991, Ball and Owsley 1993) and prospective studies (Owsley *et al.* 1998b, Sims *et al.* 2000, Rubin *et al.* 2007), as well as demonstrating strong associations with performance in driving simulators (Hoffman *et al.* 2005), closed road (Wood and Troutbeck 1994) and on-road tests (Duchek *et al.* 1998, Myers *et al.* 2000). Salthouse and colleagues (1996) theorised that age-differences in performance on specific tasks such as the UFOV could, in many cases, be parsimoniously explained by fundamental cognitive mediators such as sensory function and processing speed.

Hazard perception is the capacity of drivers to identify and respond to dangerous situations (Horswill *et al.* 2008). It involves a number of processes, including detection of a potential hazard, appraisal of the hazard as a threat followed by selecting and implementing an appropriate response (McKenna and Horswill 1999). McKenna and Crick (1991) argue that the critical aspect of hazard perception is processing the visual scene. Video-based hazard perception tests have been developed to mimic traffic situations where crashes are most likely to occur and are now mandatory aspects of licensing tests for new drivers in some jurisdictions.

Detection of change, often described as change blindness, is a failure to notice changes made to an object or a scene during a saccade, flicker, blink, or movie cut (Simons and Rensink 2005). Researchers have shown that change blindness occurs in response to a range of stimuli including photographs, computer-generated natural scenes, artificial displays, motion pictures, and even people during interpersonal interactions (Rensink 2002).

Specifically, the inability of drivers to effectively detect changes in a dynamic environment, such as a busy intersection, may correspond to an important visual attention failure (Caird *et al.* 2005). Older adults have also been shown to be slower than younger adults to perceive changes to photographs of driving scenes (Pringle *et al.* 2001). The Hazard Change Detection Task (Wetton *et al.* 2010) used in the present study takes advantage of this phenomenon by measuring how long drivers take to identify a hazard (that repeatedly appears and disappears) in an image of a traffic scene, taken as an indication of their ability to detect dangerous elements in the road environment. It has not been validated against an on-road driving assessment but has been shown to correlate with hazard detection ability in older drivers (Wetton *et al.* 2010).

The first aim of the present study is to evaluate the relative importance of widely used visual screening measures compared with cognitive predictors of the capacity to drive safely because current screening practices focus almost solely on visual function. We hypothesised that cognitive function would be at least as predictive as visual function of poor performance on validated measures of driving risk. Second, we aimed to evaluate whether cognitive speed was the primary cognitive ability underlying the more general association between cognitive tests and driving risk or whether executive function, spatial ability, working memory or visual closure, contribute additional unique variance. Third, as unsafe driving increases with chronological age (Anstey and Wood 2011), we were interested to determine whether the cognitive and visual predictors explained variance in the capacity to drive safely beyond that explained by chronological age alone. Similarly we estimated the extent to which cognitive factors and measures of the capacity to drive safely shared age-related variance.

2 Material and methods

2.1 Participants

Initially, 308 older drivers were recruited via an information sheet mailed to 2707 individuals on the Canberra electoral roll (response rate of 11.38%) inviting them to participate in a study of older drivers (voting is compulsory in Australia). This response rate is similar to that of other studies conducted on driving in Australia (Wood *et al.* 2008). After giving informed consent, assessments were conducted at a laboratory at the Australian National University. The study was approved by this institution's Human Research Ethics Committee. Three participants were excluded from the present study because they scored below the cut-off for probable dementia on the Mini-Mental State Examination (MMSE) (i.e. <24 (Folstein *et al.* 1975, Folstein *et al.* 1983)). Eight participants were excluded as they did not complete a large number of tests and questionnaires due to health or technical reasons. The remaining 297 participants all completed one or more of the driver screening instruments (260 completed all three and 37 completed one or two). Missing data on screening instruments was due to technical errors or due to participants not completing the tests or refusing to finish tests. They were aged 65 to 96 (M = 75.10, SD = 7.00) and 66.20% were male.

2.2 Procedure

Participants were tested individually in a single session of approximately 2-3 hours, including breaks to minimise fatigue. They completed the MMSE and a range of cognitive and vision tests, followed by the Useful Field of View test, the Hazard Perception Test, and the Hazard Change Detection Task. Prior to the testing session participants completed a questionnaire detailing demographic information, the SF36 scale as a measure of health (Ware *et al.* 1994), and driving behaviour in a questionnaire adapted from previous studies (Wood *et al.* 2008, Anstey *et al.* 2009).

2.3 Measures

A full list of the measures is included in Table 1.

2.3.1 Cognitive Measures

The cognitive test battery was designed to measure visuo-cognitive processing abilities that may theoretically be linked with driving abilities and/or accident risk (Anstey *et al.* 2005b). Visual processing speed was included as this is related to several of the other abilities important for driving (eg. executive function, working memory) and has been shown to have independent associations with driving outcome measures. Components of executive function that were considered important to driving (Miyake *et al.* 2000) included task switching and strategic working memory, although it is acknowledged that the general construct of executive function is difficult to define and in factor analytic studies is difficult to distinguish from fluid and working memory abilities (Salthouse 2005). Measures of visual closure were included because it was hypothesised that the ability to extract visual images from backgrounds would be important for hazard perception and hazard change detection. Visual closure has also been shown to be strongly related to driving performance (Staplin *et al.* 2003a, Staplin *et al.* 2003b, Ball *et al.* 2006). Measures of visual working memory were included because the capacity to retain visual information in memory whilst processing is required during the driving task.

2.3.1.1 Spatial ability

Spatial ability was measured by tests of mental rotation and transformation using the card rotation test and the paper folding test, both adapted from French et al.(1963). In the *Card Rotation* test participants had to decide whether each of the eight rotated sample figures were flipped or non-flipped versions of the target figure. Participants were asked to complete as many items as possible in three minutes. In the *Paper Folding* task, participants were shown a schematic of a square piece of paper being folded and then punched through, with stages depicting between one and three horizontal, vertical or diagonal folds. Participants had to select which of five alternatives depicted the pattern of holes that would be present in the unfolded square of paper. They were instructed to complete as many as possible of 10 items within three minutes.

2.3.1.2 Visual Closure

Visual closure was assessed with tests adapted from French and colleagues' 1963 battery of factor referenced cognitive tests. *Gestalt Completion* included 15 incomplete pictures and required participants to identify as many of the depicted objects as possible within three minutes. *Snowy Pictures* comprised black and white line drawings obscured by a medium density random noise mask (the 'snowy' pattern). Participants were given three minutes to work through as many of 15 items as possible. The *Concealed Words* test measures flexibility of closure, and involves identifying printed black and white words from which significant portions have been randomly erased. Participants were asked to identify as many as possible of 16 concealed words within a three minute period.

2.3.1.3 Perceptual Speed, task switching and visual search

Perceptual speed was measured with Part A of the Trail Making task, a number comparison task, a number and symbol cancellation task, and a modified version of the Wechsler Digit Symbol matching task (Wechsler 1981). Task switching was measured with Trails B. The *Trails A* and *Trails B* tests comprised a computerised version of the Trail Making Test (Reitan 1958) requiring participants to press on 20 numbered circles in numerical (part A) or alternating numerical and alphabetical order (part B) as quickly as possible. A red line progressively connected the circles as the participant pressed on them. A *Number Comparison* task was adapted from French and colleagues (1963). Participants had to compare two columns of 48 numbers and identify as many number pairs that differed as possible within 90 seconds. Participants were also given a computer-administered *Digit symbol matching* task, based on Salthouse's (1994) adaptation of the Wechsler Digit Symbol Subscale (previously described in Anstey *et al.* 2006). A two–row code table with nine digits and nine corresponding symbols was presented at the top of the screen. For each of the 20 trials participants were asked whether symbol-digit pairs were matches or non-matches with the code-table by pressing on an appropriate button on the touch screen. Accuracy and reaction time for each trial was recorded. *Letter Cancellation* tasks were adapted from Moran and Mefferd (1959). Participants were required to cross out as many 'D's as possible in 15 rows of capital letters in 45 seconds.

2.3.1.4 Colour Choice Reaction Time (CRTC)

A computerised inhibition choice reaction task previously shown to discriminate safe from unsafe drivers (Wood *et al.* 2008). Targets (red or blue cars) were presented in one of four quadrants of a grid on screen. Participants were instructed to respond to red targets appearing in the top right cell by pressing a right hand button, red targets in the top left required a response using a left hand button, and those in the bottom right and left cells required a foot response using right and left pedals respectively. Blue cars occurred on 11.1% of trials, and required a response inhibition (i.e., not pressing any buttons). The computer recorded reaction times and accuracy for each of 60 trials.

2.3.1.5 Working memory

Digit span backwards was adapted from the Wechsler Adult Intelligence Scale-III (Wechsler 1997). A score was calculated as the sum of all correct responses. A Visual Working Memory task (Spatial Memory) constructed for this study involved the presentation of targets at different positions in a six-cell or a nine-cell grid at a rate of one per second. The grid was then replaced on screen by a distractor task involving a short sentence that participants were required to read aloud. Participants were then asked to press the appropriate cells in an empty grid in the same order as the targets had appeared. Presentation sequences ranged from two to nine targets, with two trials for each sequence. The test was scored as the number of correct responses. Finally, a computerised *Lettersets* task adapted from Anstey & Smith (1999) involved the presentation of pairs of letter strings, ranging in length from two to ten letters. The second string contained all but one of the same letters as the first string, with the letters presented in a different order (e.g., LRND – RDMN). The second string remained on screen until participants indicated the two unique letters from each string (L and M in the example above).

2.3.2 Vision Measures

Static visual acuity was tested with participants wearing their standard distance prescription, using a high and low contrast Bailey-Lovie (logMAR) chart at a working distance of 2.4m under the recommended illumination conditions (Bailey and Lovie 1976). Visual acuity under both high and low contrast condition was scored on a letter by letter basis, where each letter correctly identified represented a score of 0.02 log units. Letter contrast sensitivity was determined using Pelli-Robson charts under the recommended testing conditions (Pelli *et al.* 1988). Participants were instructed to look at a line of letters and to guess the letter when they were not sure. Each letter was scored as 0.05 log units.

2.3.3 Measures of Capacity to Drive Safely

For the present study subtest two of the UFOV® was adapted, as it has demonstrated high reliability and validity (Owsley *et al.* 1998a, Ball *et al.* 2006), and has been used without subtests one or three in other large studies on driver screening (Ball *et al.* 2006). Participants attend to dual targets presented simultaneously on screen: a white, two-dimensional block figure of a car or truck at the centre of the screen with a second car figure presented 10cm (radially) from the central fixation point at 0º, 45º, 90º, 135º, 180º, 225º, 270º, or 315º from the vertical. Following presentation, a random noise mask was shown and participants were instructed to indicate: (a) which vehicle was presented in the centre of the screen by pressing a picture of a car or truck; and (b) where the second car was located by pressing one of the eight possible locations onscreen.

2.3.3.1 Hazard Perception Test

This test required participants to anticipate potential traffic conflicts in video clips of traffic scenes filmed from the driver's point-of-view (Wetton *et al.* 2009) by pressing the relevant area of the touchscreen whenever they identified a potential incident. Twenty-two traffic conflicts (across 20 traffic clips of between 15-40 seconds duration) were selected on the basis that (1) there were anticipatory cues available, and (2) the conflict became unambiguous such that nearly all participants would be expected to respond eventually. The software recorded a response time for each potential conflict (starting from the first moment that the potential conflict was detectable) and these were averaged to obtain an overall hazard perception response latency. Performance on this test has been validated against self-reported crashes using the sample on which the current study is based (Horswill *et al.* 2010a).

2.3.3.2 Hazard Change Detection Task

The Hazard Change Detection Task (Marrington *et al.* 2008) was used to measure participants' ability to detect the presence of hazards independent of other factors (e.g., speed). The task used pairs of still images of traffic scenes, which were displayed on a computer screen using the flicker paradigm (Wetton *et al.* 2009). Each pair of scenes (59 trials in total) contained an original and an altered image which were displayed for 250ms, and this was alternated with a gray mask (which was displayed for 80 ms). Participants were asked to identify the difference between the two pictures by pressing on the screen as soon as they noticed the difference and the outcome measure was the mean reaction time for correct trials.

2.4 Statistical analysis

Data were screened for outliers and missing values. For reaction time measures, values above or below three standard deviations from the mean were removed using techniques previously described (Anstey *et al.* 2005a). Missing data on the predictor variables were imputed using the Maximum Likelihood technique in SPSS 18.0 with age, the MMSE and all cognitive variables included as predictors. There were 27 participants with missing data on Gestalt completion, 11 on Trails A, 10 on Trails B, 10 on choice reaction time, five for card rotations, one for visual search, number comparison and concealed words. Imputation is recommended to reduce bias caused by data not missing at random (Schafer and Graham 2002).

The battery of tests of cognitive and visual function was reduced using Principal Axis Factoring (PFA) analysis with oblimin rotation and Kaiser Normalization. PFA does not assume multivariate normality and hence is appropriate for use with reaction time data that is skewed. The threshold for extraction was the number of eigenvalues larger than 1, and loadings higher than 0.32 were interpreted (Tabachnick and Fidell 2007). Factor scores were saved from the analysis using the Bartlett method.

3 Calculation

Hierarchical multiple regression was used to address each of the main research questions. First, the relative importance of the cognitive and visual factors for predicting performance on the driving screening measures were evaluated in a regression model by entering all the cognitive factors and vision after adjusting for age, sex and health measured by the total SF36 score. Interactions between age and the cognitive and visual factors, and between sex and the cognitive and visual factors were also tested to determine whether the effects of the factors were moderated by age or sex. The significance of age as a predictor of the capacity to drive safely (independent of vision and cognitive performance), and the proportion of age-related variance shared by the cognitive factors, were evaluated by conducting hierarchical regression analyses both adjusting for age and then including age after the cognitive and visual factors. Understanding the role of age in predicting the capacity to drive safely is important because many jurisdictions impose age-based testing of older drivers. A similar approach was used to evaluate the amount of variance in vision that uniquely predicted the capacity to drive safely independent of cognition.

4 Results

4.1 Descriptive statistics and intercorrelations

The descriptive statistics and intercorrelations among variables are shown in Table 2. All cognitive and visual measures showed moderate to strong associations with chronological age and the driver screening instruments also showed moderate associations with age. The three driver screening measures also were individually correlated with the majority of the measures of cognitive and visual function.

4.2 Exploratory factor analysis of visual and cognitive measures

Factor analysis of the cognitive and vision measures produced a solution with five eigenvalues greater than 1 so a five factor solution was accepted. The pattern matrix for the final model is shown in Table 3. The first factor was defined by Digit-Symbol Matching RT, Number comparison, CRTC (both the RT and number correct measures), Visual search, and Trails B, suggesting these measures define a latent variable of fluid-executive abilities involving speed, visual attention and task-switching. It was therefore called ‘Speed/Executive’ (Speed/exec). The second factor to emerge was the visual acuity/visual contrast sensitivity factor (Vision), followed by Visual Closure (Closure) which was defined by the three measures of closure as planned. Fourth, the spatial measures plus Trails B loaded onto a factor called ‘Spatial’. Fifth, a working memory factor (Workmem) was indicated by loadings of DSB, Spatial n-back, Letter sets, and Concealed words. The factor analysis explained 52.04% of the variance in the measures. Factor intercorrelations are also shown in Table 3. There was a moderate sized correlation between Speed/Exec and Vision, Spatial and Workmem, and between Workmem and Spatial. Vision had moderate associations with the other cognitive factors.

4.3 Evaluation of potential sample bias due to participants not completing all outcome measures

Of the 37 participants who did not complete all three outcome measures, 24 completed the UFOV, 20 completed the HPT and 27 completed the HCDT. Analysis of the subjects who completed fewer than three of the screening tests compared to those who completed all three showed that non-completers were older (77.81 vs 74.68, $t(295) = 2.20$, $p < .01$) had fewer years of education (12.65 vs 14.61, $t(291) = 2.83$, $p < .01$) but they did not differ in their MMSE scores or vision scores. When compared on the cognitive factors, those who did not complete all three measures of the Capacity to Drive Safely performed worse on the Speed/Ex ($t(291) = -2.9$, $p < .01$) and Spatial factors ($t(291) = 5.21$, $p < .01$).

4.4 Regression of Measures of capacity to drive safely on cognitive and visual factors

Table 4 shows the results of hierarchical multiple regression of the cognitive and visual factors adjusting for age and sex. Age was significantly associated with performance on UFOV and HCDT, and gender was associated with HCDT (males faster than females). Speed/Exec and Spatial were associated with UFOV, HPT and HCDT. Vision was only associated with HPT. Closure was not associated with any of the outcome measures. Working memory was associated with UFOV only. Health was not correlated with UFOV, HPT or HCDT and inclusion of the SF36 score in the regression models did not change the findings (results not shown). Over 40% of variance in UFOV, 44% of variance in the HCDT and over 30% of variance in the HPT was explained by the cognitive and visual measures.

The age by Vision interaction was non-significant in all models. Age and cognitive ability interactions were all non-significant except for the age by Speed/Exec interaction which was significant for the HPT (beta 1.91, $p < .01$) and accounted for 2% of the variance in HPT. Evaluation of the interaction showed that the association between HPT and Speed/Exec was non-significant in adults aged over 85. Sex by cognitive ability interactions and the sex by vision interaction were non-significant in all regression models.

4.5 Evaluation of age-related variance in screening measures explained by vision and cognitive factors

For the UFOV, age explained 26% of the variance and vision and cognition only explained an additional 15% of variance. When age was entered after the visual and cognitive factors it explained about 4% of the variance, indicating that about 85% of age-related variance in the UFOV was explained by the cognitive and vision factors (i.e. (100-[((4/26)x100)]). Age explained 16% of variance in the HPT, and about 95% of this was shared with the cognitive and vision factors. Age no longer made a statistically significant contribution to performance on the HPT after adjusting for the cognitive and visual factors. Age explained 28% of variance in HCDT and 83% of this was shared with the cognitive and vision factors.

Table 5 shows hierarchical regressions that evaluate the extent to which the contribution of vision is shared with the cognitive factors. Vision explained about 3% of variance in HPT after controlling for age and the cognitive factors, but made minimal unique contribution to UFOV and HCDT in the same models.

5 Discussion

The present study investigates a component of the Multifactorial Model of Driving Safety to specifically increase understanding of how cognitive and visual function independently and jointly explain performance on validated measures of the Capacity to Drive Safely. As expected, a large proportion of variance in the outcome measures was explained by age. The cognitive and vision factors shared between 83% and 95% of variance in the outcome measures with chronological age indicating that chronological age is an index of cognitive and visual changes that affect driving in late-life.

The first research question we aimed to investigate was the relative importance of visual acuity and contrast sensitivity and cognitive abilities, in relation to driving risk. The cognitive factors accounted for a far greater proportion of variance, although it should be noted that there were many more cognitive than visual measures included. This finding may suggest that relying on visual acuity rather than cognitive screening is not the optimal approach to assessment and screening of older drivers. Ideally, the most sensitive visual and cognitive function measures would be included in evaluations of driver safety. Although visual acuity is only one domain of visual function and there are other visual abilities with much stronger associations with driving performance, such as motion sensitivity (Wood *et al.* 2008) it is the domain currently assessed in driver licensing in many jurisdictions.

Visual function measured by standard measures of acuity and contrast sensitivity was uniquely associated with performance on the HPT but not the other outcome measures once the cognitive factors and age had been adjusted for. Visual contrast sensitivity measured by the Pelli Robson test has previously been associated with the HPT (Marrington *et al.* 2008, Horswill *et al.* 2009). While some previous studies have shown very high covariance between visual acuity and processing speed measures suggesting a common underlying process (Salthouse *et al.* 1996) the current study differentiates the functional roles of visual and cognitive function in relation to driving outcome measures. It is likely that more sensitive vision measures across a range of different visual functions including motion sensitivity and peripheral vision would explain a larger proportion of unique variance in driving ability measures.

The second research question we aimed to address was the relative importance of cognitive speed versus other cognitive abilities, in explaining performance on the measures of Capacity to Drive Safely. However in our factor analysis, a pure speed measure did not emerge, but rather, processing speed and executive type measures formed a single factor suggesting that these measures share common variance and are inextricably linked. Consistent with previous research, (Daigneault *et al.* 2002, Decker *et al.* 2007) this factor was strongly associated with our outcome measures and did have the largest effect on UFOV and HCDT. We conclude therefore that processing speed and speeded executive tasks such as Trailmaking are the strongest correlates of integral driving skills in later life (Salthouse 2005). However, this study also found that Spatial ability was significantly associated with performance on all outcome measures, in a model that adjusted for Speed/Exec. Working memory was also important for performance on UFOV and HCDT, as both tasks involve a memory load. As driving involves judgement of location, distance and speed and general spatial awareness, the consistent finding that spatial ability was associated with the Capacity to Drive Safely finding has strong ecological validity. Overall, these findings indicate that visual-cognitive abilities known to decline with age and which have a strong genetic component (Finkel *et al.* 2004) are those that also predict driving skills, and that a wide range of cognitive abilities are involved in safe driving.

The third research question we addressed was the extent to which age-related variance in our measures of the Capacity to Drive Safely could be explained by visual and cognitive function. Consistent with previous research (Anstey and Wood 2011), measures of Capacity to Drive Safely were negatively associated with chronological age. Similarly, all individual cognitive and visual measures showed negative bivariate correlations with age.

However, investigation of the interaction between age and Speed/Ex showed that among the oldest participants in the sample, the correlation between HPT response time and Speed/Ex was no longer significant. This may be been due to the smaller numbers of participants in this age-range, and the highly selected sample, particularly at these very old ages. Much larger studies of adults aged 85 and older is required to fully understand the interrelationships between HPT response time and cognitive function among the oldest old. It is clear that the Capacity to Drive Safely declines in normal ageing, although it is only when a threshold is reached that this becomes problematic. Identification of this threshold is the focus of research into screening instruments and older driver assessment batteries (cf. Wood *et al.* 2008). The current project contributes to the evidence base that will inform individualized neuropsychological assessment of at-risk older drivers.

Although most of the age-related variance in performance on measures of safe driving capacity was shared with the cognitive measures, there were still independent effects of cognitive function on all the outcome measures. This shows that chronological age alone is adequate for predicting driver risk, and that cognitive screening will improve assessments based purely on age and vision.

Future advances in driver screening and interventions require the development of more sophisticated models of how factors inter-relate to influence driving performance under different conditions. Such models and methodologies may then be applied to other disorders involving neuropsychological impairment. Future research may identify specific risk profiles associated with specific neurological conditions occurring with greater prevalence in late life such as Parkinson's Disease (Wood *et al.* 2005), stroke (Devos *et al.* 2011) and Alzheimer's Disease (Carr *et al.* 2000).

The present study had several limitations. Although the electoral roll was used as a sampling frame, the response rate was low and this is likely to have led to sample bias towards a high functioning group. Hence the results are likely to underestimate the true strength of associations among measures. Analysis of the group who did not complete all outcome measures showed they were older, less educated and had poorer performance on the two cognitive factors with the strongest associations with the driving outcome measures. This suggests that a limitation of the screening measures used is that they may be too challenging or demanding for individuals who are at greatest risk of unsafe driving. Hence researchers need to develop measures that are acceptable to the widest possible range of older adults who need to be screened.

The study lacked an on-road driving test or driving simulator to validate the screening measures, and the HCDT has not been validated against an on-road test. There are many types of errors that older adults make while driving (Wood *et al.* 2009a) and it is unclear at this stage whether the UFOV, HPT, and HDCT are indicative of similar or different types of on-road driving errors. Further research is required to evaluate these outcome measures jointly against both crash data and on-road driving assessments. The study was also limited in the range of visual function measures included. Previous research has shown that visual measures of motion sensitivity (Wood *et al.* 2008) are strong predictors of on-road driving performance, however we chose to include only standardised measures of visual function, that are more likely to be administered in a driver licensing situation.

The current study has several practical implications. Our results describe abilities that are strongly related to the Capacity to Drive Safely and demonstrate that on average these abilities decline with age. However this does not imply that age can be used as an indicator of driving ability. At the individual level, assessment of actual visual and cognitive function is likely to be a fairer and more accurate indicator of driving ability than chronological age. There are large individual differences in abilities even at older ages and individual assessment is required to determine a person's actual visual and cognitive abilities. Our results may also be used to guide the development of driving environments, that enable older adults to drive safely despite changes in cognitive and visual function. Finally, understanding the key abilities involved in safe driving is essential for the development of training interventions to improve driver skill and maintain safe driving for as long as possible.

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Table 1
Tests and Measures used to Assess Driving Safety

Measurement Domains	Skills	Test(s)
Cognitive		
	Spatial ability	Card Rotation Paper Folding
	Visual Closure	Gestalt Completion Snowy Pictures Concealed Words
	Task switching Perceptual speed Visual search	Trail making test (A,B) Number comparison task Digit symbol matching (computer based) Letter cancellation tasks
	Choice Reaction Time	Computerised Colour CRT test
	Working Memory	Digit-Span backwards (adapted from WAISIII) Visual working memory task Lettersets task
Vision		
	Static visual acuity	Bailey-Lovie (logMAR) chart
Capacity to Drive safely		
	Useful field of view	Subtest 2 of the UFOV test
	Hazard perception	Hazard Perception Test
	Hazard change detection	Hazard Change Detection Task

Table 2

Means, Standard Deviations, and Correlations for Demographic, Cognitive, Visual, and Outcome Variables (N = 270-297)

Variable	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Age	75.11	7.00																							
2. Gender	n/a	n/a	.06																						
3. Education	14.35	3.86	-.11	.24**																					
4. Card rotation	31.62	12.09	-.27**	.25**	.13*																				
5. Paper folding	3.47	1.88	-.24**	.08	.16**	.41**																			
6. Gestalt completion	5.53	3.31	-.26**	-.14*	.11	.21**	.33**																		
7. Snowy pictures	6.16	2.24	-.28**	-.16**	.02	.20**	.26**	.50**																	
8. Concealed words	8.34	2.33	-.19**	-.04	.01	.19*	.19**	.45**	.41**																
9. Trails A	37.55	11.94	.39**	-.02	-.07	-.31*	-.29**	-.19**	-.26**	-.21**															
10. Trails B	80.83	35.78	.50**	.00	-.13*	-.47*	-.39**	-.27**	-.23**	-.31**	.55**														
11. Number comparison	20.61	5.53	-.31**	-.14*	.05	.29**	.15*	.17**	.35**	.29**	-.39**	-.40**													
12. Digit symbol matching	2.10	0.42	.44**	.12*	-.16**	-.38**	-.34**	-.26**	-.25**	-.30**	.50**	.67**	-.59**												
13. Letter cancellation	89.46	18.13	-.37**	-.06	.11	.32**	.22**	.17**	.28**	.14*	-.32**	-.47**	.52**	-.60**											
14. CRTC accuracy [a]	56.21	4.06	-.32**	-.04	.08	.20**	.14*	.15**	.08	.13*	-.27**	-.35**	.24**	-.53**	.28**										
15. CRTC reaction time	0.98	0.16	.41**	-.05	-.13*	-.41**	-.24**	-.22**	-.22**	-.23**	.38**	.56**	-.38**	.65**	-.55**	-.36**									
16. Digit span backwards	6.91	2.26	-.30**	-.07	.11	.31**	.25**	.25**	.23**	.37**	-.23**	-.41**	.31**	-.34**	.22**	.13*	-.27**								
17. Spatial memory	6.05	1.90	-.21**	.07	.19**	.26**	.21**	.09	.02	.22*	-.31**	-.37**	.32**	-.42**	.32**	.23**	-.34**	.30**							
18. Letter sets	17.62	7.18	-.40**	-.03	.14*	.33**	.35**	.20**	.23**	.33*	-.41**	-.52**	.38**	-.54**	.35**	.35**	-.39**	.42**	.39**						
19. Pelli-Robson	1.69	0.12	-.52**	-.06	.08	.21**	.17**	.13*	.19**	.19**	-.23**	-.33**	.20**	-.31**	.34**	.19**	-.41**	.17**	.14*	.26**					
20. LogMAR (high)	0.05	0.11	.41**	-.03	-.02	-.24**	-.19**	-.25**	-.24**	-.34**	.25**	.34**	-.20**	.31**	-.31**	-.11	.32**	-.17**	-.18**	-.26**	-.40**				
21. LogMAR (low)	0.27	0.13	.43**	-.08	-.07	-.25**	-.19**	-.25**	-.25**	-.34**	.24**	.34*	-.19**	.30**	-.30**	-.13*	.36**	-.17**	-.16**	-.22**	-.46**	.87**			
22. UFOV [b]	131.67	101.94	.50**	-.04	-.12*	-.38**	-.23**	-.18**	-.21**	-.25**	.43**	.51**	-.28**	.51**	-.35**	-.36**	.46**	-.29**	-.33**	-.47**	-39**	.36**	.31**		
23. HPT [c]	5.55	0.96	.39**	-.09	-.22**	-.32**	-.36**	-.17**	-.24**	-.23**	.32**	.42**	-.20**	.37**	-.26**	-.12	.45**	-.29**	-.16**	-.34**	-.35**	.37**	.36**	.33**	

24. HCDT [d]	8.03	2.58	.49**	-.14*	-.17**	-.41**	-.33**	-.29**	-.26**	-.19**	.45**	.51**	-.30**	.50**	-.36**	-.32**	.46**	-.30**	-.28**	-.39**	-.34**	.29**	.30**	.47**	.43**

[a] CRTC = Colour Choice Reaction Time
[b] UFOV = Useful Field of View test
[c] HPT = Hazard perception test
[d] HCDT = Hazard change detection task
*p < .05.
**p < .01.

Table 3

Pattern matrix from factor analysis of cognitive and visual function tests (n = 297)

	Speed/Exec[a]	Vision[b]	Closure[c]	Spatial	Wkmem[d]
Visual search	0.747	-0.101	0.092	0.007	-0.148
Number comparison	0.646	0.05	0.192	0.17	0.189
CRTC accuracy[e]	0.424	0.014	-0.064	-0.074	0.069
Snowy pictures	0.185	0.011	0.784	-0.05	-0.044
Card rotation	0.161	-0.053	0.015	-0.478	0.041
Digit span backwards	0.054	0.009	0.074	-0.142	0.47
Gestalt completion	-0.052	-0.062	0.521	-0.222	0.113
Concealed words	-0.074	-0.207	0.357	0.073	0.516
Paper folding	-0.076	0.003	0.125	-0.7	0.017
Trails A	-0.352	0.042	-0.025	0.202	-0.143
Trails B	-0.398	0.115	0.055	0.359	-0.198
CRTC reaction time[e]	-0.601	0.162	0.01	0.171	0.063
Digit symbol matching	-0.765	0.018	0.007	0.098	-0.14
Letter sets	0.27	-0.023	-0.039	-0.213	0.401
Spatial memory	0.265	-0.029	-0.193	-0.087	0.362
Pelli Robson	0.248	-0.391	0.005	-0.062	-0.074
LogMAR (low)	0.069	1.024	0.009	-0.025	0.007
LogMAR (high)	0.038	0.873	-0.001	-0.03	-0.066
Factor Intercorrelations					
Wkmem	0.42	-0.225	0.246	-0.391	
Closure	0.114	-0.266			
Vision	-0.364				
Spatial	-0.469	0.327	-0.176		

[a] Speed/Exec = Executive-Speed
[b] Vision = Visual acuity
[c] Closure = Visual closure
[d] Wkmem = Working memory
[e] CRTC = Colour Choice Reaction Time

Table 4

Hierarchical Regression of Driver Screening Measures of Vision and Cognitive Factors

	UFOV[a] (*n* = 274)		HPT[b] (*n* = 269)		HCDT[c] (*n* = 276)	
	β	Incr[d]. R^2	β	Incr. R^2	β	Incr. R^2
Step 1						
Age	.243**		.119		.233**	
Sex	-.075	.251**	-.054	.158**	-.146**	.276**
Step 2						
Speed/Exec	-.296**		-.146*		-.291**	
Vision	.056		.193**		.035	
Closure	.002		-.033		-.054	
Spatial	-.160**		.257**		.250**	
Wkmem	-.160**	.410**	.075	.300**	-.090	.440**

Note incr. = incremental

[a] UFOV = Useful Field of View test

[b] HPT = Hazard perception test

[c] HCDT = Hazard change detection task

[d] incr = incremental

* $p < .05$

** $p < .01$

Table 5

Hierarchical multiple regression models evaluating shared variance among age, cognitive and vision factors

	UFOV [a]	HPT [b]	HCDT [c]
	Incr [d]. R^2	Incr. R^2	Incr. R^2
n	274	269	276
Model 1			
Age	.257**	.158**	.276**
Vision/Cognitive	.410**	.300**	.440**
Model 2			
Vision/Cognitive	.370**	.289**	.393**
Age	.410**	.300	.440**
Model 1			
Age	.250**	.146**	.244**
Cognitive	.401**	.267**	.419**
Vision	.405	.297**	.421
Model 2			
Age	.250**	.146**	.243**
Vision	.269**	.203**	.259*
Cognitive	.405**	.297**	.421**

[a] UFOV = Useful Field of View test

[b] HPT = Hazard perception test

[c] HCDT = Hazard change detection task

[d] incr. = incremental

* $p < .05$

** $p < .01$