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The impact of cognitive functioning on driving performance of older persons in comparison to younger age groups: a systematic review.

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Abstract

Older drivers are at a severely higher risk for motor vehicle crash involvement. Due to the global aging of the population, this increased crash risk has a significant impact on society, as well as on an older individual's quality of life. For this reason, there is a need for understanding how normal age-related changes in cognition and underlying brain dynamics impact driving performance to identify the functional and neurophysiological biomarkers that could be used to design strategies to preserve or improve safe driving behavior in older persons. This review provides an overview of the literature on age-related changes in cognitive functioning and brain dynamics that impact driving simulator performance of healthy persons. A systematic literature search spanning the last ten years was conducted, resulting in 22 eligible studies. Results indicated that various aspects of cognition, most importantly executive function, complex attention, and dual tasking, were associated with driving performance, irrespective of age. However, there was a distinct age-related decline in cognitive and driving performance. Older persons had a more variable, less consistent driving simulator performance, such as more variable speed adaptation or less consistent lane keeping behavior. Only a limited number of studies evaluated the underlying brain dynamics in driving performance. Therefore, future studies should focus on implementing neuroimaging techniques to further unravel the neural correlates of driving performance.

Keywords: driving performance, healthy aging, cognition, dual tasking, neuroimaging, driving simulator

1 Introduction

With the continued aging of the population, the proportion of older persons in the possession of a driver's license is expected to increase further in the coming years (Eby et al., 2008). Yet, older drivers have a higher risk of involvement in a fatal or injury-inflicting motor vehicle accident, especially when they only drive a limited number of kilometers per year (Hakamies-Blomqvist, 2004; Langford et al., 2006). Additionally, research has indicated that older drivers are more likely to be involved in crashes in which they are deemed to be responsible for the crash (Baldock et al., 2002; Ichikawa et al., 2015; Kubitzki & Janitzek, 2009; Lombardi et al., 2017). Nevertheless, driving remains an important part of the life of older persons, as this warrants mobility and functional independence. As such, driving cessation at a higher age could be a risk factor for depression, or for an accelerated admission into a retirement facility (Chihuri et al., 2016; Siren & Haustein, 2015; Windsor et al., 2007). For this reason, it is of utmost importance to older persons that they can drive safely for as long as possible. Therefore, this systematic review aims to synthesize the literature regarding the impact of normal age-related changes in cognition and brain dynamics on driving performance in order to provide additional insights that could help create strategies to preserve and improve older persons' driving performance.

Due to normal aging processes visual, motor, and cognitive abilities essential for driving can deteriorate (Harada et al., 2013; Salthouse, 2019). Adequate cognitive function is needed for appropriate decision-making while driving. It facilitates the selection and interpretation of relevant information to generate a correct driving response. An age-related decline in cognitive function, such as a deterioration of executive function, attention, dual tasking ability, visuo-spatial abilities, processing speed, or memory can all negatively affect an everyday activity such as driving (Anstey & Wood, 2011; Cuenen et al., 2015; Cuenen et al., 2016; Salthouse, 2019; Wagner et al., 2011). Knowing how driving performance is affected by this cognitive deterioration is necessary for determining a preventive and interventional approach for increasing driving safety at an older age.

The cognitive domain of executive function is related to the capabilities that enable one to successfully engage in independent, appropriate, purposeful, and self-serving behavior. This includes the executive functions such as planning, working memory, inhibition, mental flexibility, and problem-solving (Chan et al., 2008; Lezak et al., 2012). Subsequently, the domain of attention has different aspects: (i) selective or focused attention, i.e. the ability to focus on specific information while ignoring distracting stimuli; (ii) sustained attention, i.e. the ability to maintain concentration over a period of time; and (iii), divided attention, i.e. the ability to focus on more than one task or stimulus simultaneously. Adequate executive and attention skills are also a prerequisite for dual- and multitasking performance, i.e. the ability to coordinate several simultaneous or serial tasks to achieve an overall goal (MacPherson, 2018). Furthermore, multitasking is also considered an essential skill for driving, as driving consists of operating the vehicle, paying attention to traffic and surroundings, possibly listening to the radio or talking to a passenger, and all of this while the driver also has to plan, execute and adapt his or her behavior in response to sudden changes in the driving environment

(Ross et al., 2019; Schlag, 2008). Visuo-spatial abilities refer to the higher-level skill of stimulus identification and localization (Strauss et al., 2006). Processing speed can be considered the time it takes to do a cognitive task, and is often assessed using reaction time tasks (Salthouse, 1996). Finally, memory refers to the processes of encoding, storing and retrieving information (Strauss et al., 2006).

All of these cognitive functions can deteriorate due to normal aging processes. Especially executive function and complex attention, which involve both selective and divided attention, seem to be very susceptible to aging effects (Harada et al., 2013; Lezak et al., 2012). Furthermore, these age-related changes in cognition can be attributed to alterations in brain structure and connectivity, i.e. reduction in grey matter volume and disruption of white matter tract integrity (Fjell et al., 2017; Sigurdsson et al., 2012; Ward, 2006). The greatest impact can be seen in frontal and medial temporal brain regions, which are both important for cognitive function and motor control (Ward, 2006). These normal age-related neural processes could also play a role in the deterioration of healthy older persons' driving performance.

Up to now, a large body of literature is available on how normal age-related changes in cognition affect driving performance. However, due to methodological variability, it remains unclear to which extent the different aspects of cognition, and underlying brain dynamics, affect driving performance in an older population. Research has indicated that current protocols for age-related medical or cognitive screening, and the potential subsequent obligation to stop driving, does not necessarily imply safer mobility for older persons (Siren & Haustein, 2015). Previous research demonstrated that in countries implementing driving license renewal screenings, motor vehicle accident rates of older drivers did not decrease after implementation of these screening procedures (Siren & Haustein, 2015). Furthermore, it was found that after implementing screening procedures, older persons were more likely to be involved in fatal accidents as a pedestrian or cyclist (Hakamies-Blomqvist et al., 1996; Siren & Meng, 2012). The lack of decreased driving related crash rates can be explained by the fact that currently used medical or cognitive screening protocols might not be suitable for evaluating driving performance of older persons. Since driving is a complex skill that requires several abilities, such as adequate visual, motor, and cognitive abilities, a single specific test is not sufficient to predict the driving performance of an older person (Karthaus & Falkenstein, 2016; Urlings et al., 2018). As the effectiveness of the currently available screening tools is unclear to date, it is necessary to consider the potential of intervention strategies, and to not underestimate an older adult's capacity to learn (Maes et al., 2017; Santos Monteiro et al., 2017). Therefore, it might be beneficial to focus on defining intervention and prevention strategies based on the impact of normal age-related changes in cognition on driving performance. Focusing on the predictive value of cognitive tests only in the context of driving license renewal procedures for older drivers, might be less significant.

The aim of this review is to present the existing literature that investigated the impact of age-related changes in cognitive function on driving performance by comparing the link between different aspects of cognition and driving performance in healthy older persons and younger age groups. Only studies evaluating driving simulator performance were included, as this makes the driving results more uniform and comparable across the included literature. Studies of the last ten years were considered in order to exclude studies that might have used outdated driving simulation technology, not comparable to the modern driving simulators currently used. The use of a driving simulator allows for a standardized, systematically controlled, and safe evaluation of a variety of driving-related measures, dual tasking capabilities while driving, and the simultaneous use of neuroimaging techniques (Aksan et al., 2016; Classen et al., 2014; Eramudugolla et al., 2016; Lee et al., 2003). Additionally, there has been positive evidence concerning the validity of driving simulators in predicting on-road driving performance in an older population (Aksan et al., 2016; Lee et al., 2003). We will evaluate to what extent specific changes in cognitive function influence simulated driving performance and how underlying brain physiology could potentially explain the deterioration in driving performance of healthy older persons. We envisage that this overview could assist in identifying the physiological and functional biomarkers that could place older persons at risk for motor vehicle crash involvement and can be used to design remedial measures to preserve or improve safe driving behavior.

2 Methods

2.1 Search methods

This systematic review is conducted and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Moher et al., 2009). Three electronic databases (PubMed, Web of Science and Scopus) were searched to identify studies of the last 10 years that examined the link between simulated driving performance and cognitive functioning in healthy older persons. The following terms were included in the search strategy: ‘a(e)ging’, ‘brain imaging’, ‘EEG’, ‘cognition’, ‘cognitive functioning’, ‘driving performance’, ‘driving’, ‘fitness to drive’, and ‘driving simulator’. Additional specific terms were added for cognitive functioning: ‘executive function’, ‘attention’, ‘perception’, ‘inhibition’, ‘reaction time’, ‘working memory’, ‘workload’, and ‘response planning’. The complete list of search terms is shown in Table 1. The full electronic search strategy for the Web of Science database is provided in the supplementary information. The last search was undertaken on July 8th, 2019. Reference lists of included studies were screened for potentially relevant studies. Duplicate studies were removed. First, two researchers (SD and KvD) independently screened studies on title and abstract to exclude studies that did not meet the inclusion criteria. The full texts were then retrieved and assessed for eligibility (see below in 2.2). Disagreements between the two researchers were resolved by discussion and consensus.

Population	**Cognition**	**Driving**
A(e)ging	Brain imaging	Driving performance
Old	EEG	Driving
Elderly	ERP	Fitness to drive
Older	Cognition	Driving simulator
	Cognitive function	
	Cognitive ability *(executive function, attention, perception, inhibition, reaction time, working memory, workload, response planning)*	

Table 1: Search terms

2.1 Eligibility criteria

To be included in this systematic review, a study had to meet the following inclusion criteria: (i) the included older and young populations were reported as healthy, based on self-report measures or other diagnostic tools, (ii) driving performance was assessed in a driving simulator, (iii) use of neuropsychological or behavioral tests to assess cognition or use of neuroimaging techniques (EEG, fMRI), (iv) studies were published in an English-language journal in the last 10 years (2009-2019). Studies were excluded if (i) automated driving or Advanced Driving Assistance Systems (ADAS) were used, (ii) the relationship between cognitive measures and driving measures was not evaluated, (iii) the study related to a case study or literature review.

2.2 Data extraction

Data were extracted and documented in a standardized data extraction form (see supplementary material). Information about study design, participants (number of subjects, age, gender, driving experience and frequency), cognitive assessment (neuroimaging, additional cognitive assessment or dual task performance testing), driving simulator outcome (driving scenario and outcome parameters), and results (driving results, cognition results, and the relationship between driving and cognition results) were documented. The pooled average and standard deviation were calculated for the demographics of all included studies.

2.3 Quality assessment

Study quality was assessed by a 15-item scale based upon the 'Strengthening the Reporting of Observational Studies in Epidemiology' (STROBE) checklist (von Elm et al., 2007). The scale was completed after consensus by the co-authors. The 15 items were divided into 3 categories: introduction, methods and results, and discussion. The complete scale can be found in Table 2. For each item, a maximum score of 2 could be awarded, with 2: a positive rating, 1: a mediocre rating, and 0: a negative rating. A mediocre rating indicated that the study only partly met the criteria of the scoring item. Scoring ranged from 0 to 30, with 30 indicating the highest possible quality. Cut-off values were set at a score of less than 22 points for poor, between 22 and 26 for medium, and 26 and higher for high methodological quality.

Introduction

1. Is the scientific context clearly explained?
2. Are the objectives clearly stated?

Methods

3. Are the setting and relevant dates (periods of recruitment, exposure, follow-up and data collection) clearly explained?
4. Are inclusion and exclusion criteria and selection of participants clearly explained?
5. Is the sample size considered adequate?
6. Are the study outcomes clearly described?
7. Is the method used in the assessment clearly described?
8. Is the method for assessment valid?
9. Are the efforts to limit potential sources of bias reported?
10. Are the statistical methods clearly described?
11. Are the statistical methods appropriate?

Results and discussion

12. Is drop-out during the study clearly described?
13. Are the characteristics of the subjects described?
14. Is there selective reporting of results?
15. Are study limitations discussed?

Table 2: Methodological quality assessment

3 Results

A detailed overview of all study results and data extraction can be found in the supplementary material (see supplementary table 4-6). Only the most prominent results are discussed in this section.

3.1 Study Selection

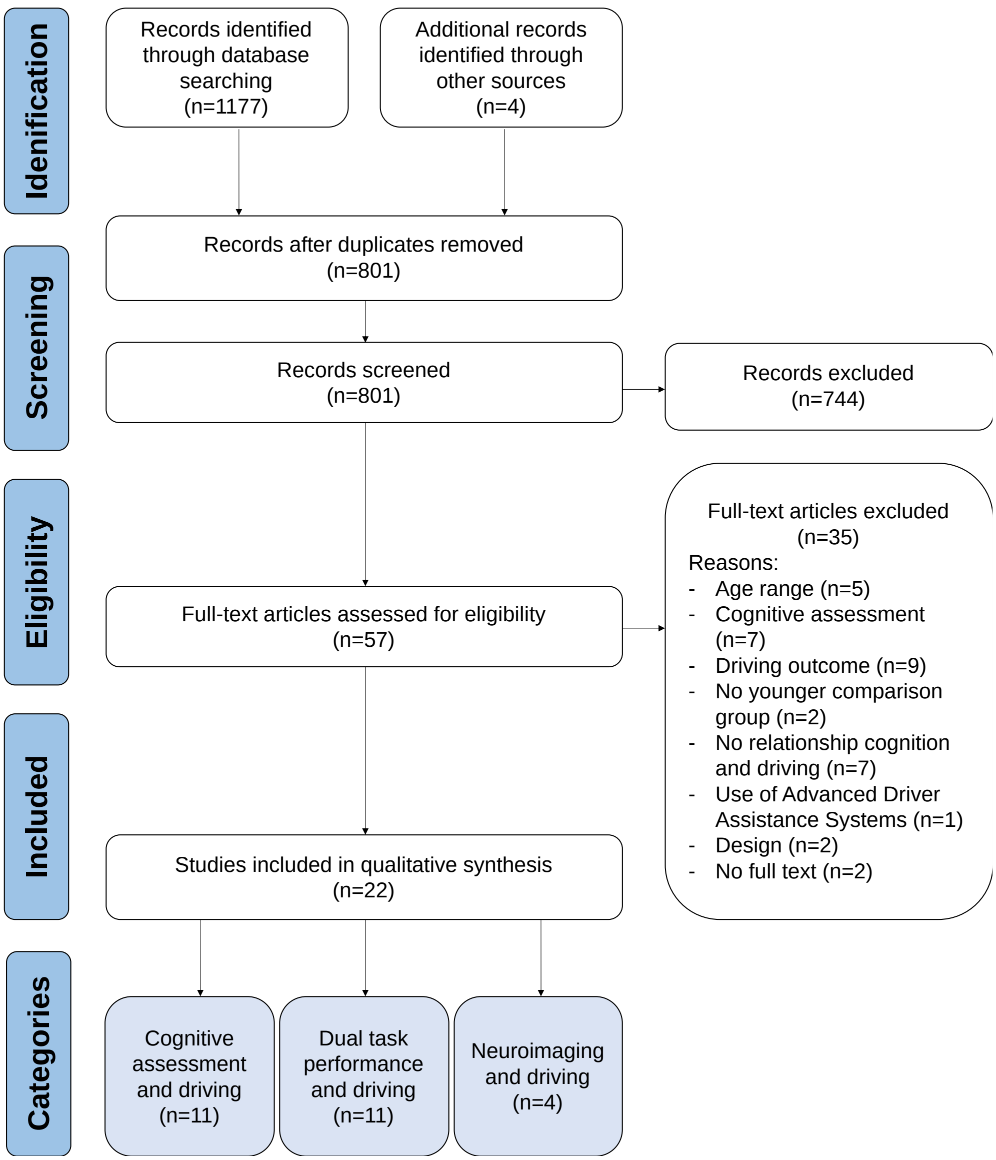

Figure 1: Flowchart: PRISMA flowchart for the study selection process.

The electronic database search yielded 1177 results. Four additional studies were identified by screening reference lists of included studies. After removal of duplicates, 801 studies remained that were screened based on title and abstract. A total of 57 studies were considered to meet inclusion criteria, and full-text versions were read to assess eligibility. Thirty-five studies were excluded (see Figure 1 for reasons of exclusion). The remaining 22 eligible studies were further subdivided into 3 categories: additional cognitive assessment, dual task performance, and neuroimaging (a study could be allocated to more than one category). Quality was assessed for these 22 studies. All studies implemented a cross-sectional design. Six studies were considered to be of high quality, another 12 studies were of medium quality, and 4 studies were considered to be of poor quality. The score of each study for all of the 15 items of the quality assessment is presented in Table 3.

	Introduction					Methods					Results and Discussion						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Score**	**Quality**
Alonso et al., 2016	2	1	2	2	2	2	2	2	1	2	2	-	1	2	2	**25**	Medium
Andrews & Westerman, 2012	2	2	2	1	2	2	2	2	1	0	1	1	2	2	2	**24**	Medium
Belanger et al., 2010	2	2	2	1	2	2	2	2	2	1	0	2	2	2	2	**26**	High
Belanger et al., 2015	2	2	2	1	2	2	2	2	2	1	0	2	2	2	1	**25**	Medium
Bunce et al., 2012	2	2	2	2	2	2	2	2	2	1	1	2	1	2	2	**27**	High
Cantin et al., 2009	2	2	2	2	0	2	2	1	2	1	1	2	2	2	1	**24**	Medium
Chen et al., 2013	0	1	2	1	0	2	2	2	1	1	1	-	2	2	1	**18**	Poor
Eudave et al., 2018	2	2	-	2	2	2	2	2	1	2	2	2	2	2	2	**27**	High
Fofanova & Vollrath, 2011	2	1	2	2	0	2	2	1	1	2	1	2	2	2	1	**23**	Medium
Getzmann et al., 2018	2	1	1	1	0	2	2	2	1	2	2	2	2	2	0	**22**	Medium
Karthaus et al., 2018a	2	2	1	2	0	2	2	2	1	2	2	-	2	2	0	**22**	Medium
Karthaus et al., 2018b	2	2	2	2	2	2	2	2	1	2	2	-	2	2	2	**27**	High
Ledger et al., 2019	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	**29**	High
Liu et al., 2011	2	2	2	2	2	2	2	2	1	1	1	-	1	1	1	**22**	Medium
Michaels et al., 2017	2	1	2	2	2	1	1	1	1	2	2	-	0	2	1	**20**	Poor
Park et al., 2011	1	1	1	1	2	1	2	1	1	1	1	-	2	1	1	**17**	Poor
Perlman, 2019	2	1	2	2	0	2	2	2	1	2	2	2	1	2	2	**25**	Medium
Pitts & Sarter, 2018	2	2	2	2	0	2	2	1	1	2	2	-	0	2	2	**22**	Medium
Rodrick et al., 2013	2	1	2	0	0	2	2	1	1	1	1	1	0	1	1	**16**	Poor
Son et al., 2011	1	1	2	2	2	2	2	2	1	1	1	2	1	2	0	**22**	Medium
Stinchcombe et al., 2011	2	2	2	2	2	2	2	2	1	1	1	2	1	2	2	**26**	High
Wechsler et al., 2018	2	2	2	2	2	2	2	1	1	2	2	2	1	2	0	**25**	Medium
2 = positive rating; 1 = mediocre rating; 0 = negative rating; - = no information (=0 score)																	

Table 3: Quality assessment

3.2 Driving simulator performance

Concerning the driving performance across the different age groups, older persons generally drove slower and at a less consistent speed than young and middle-aged adult persons (Alonso et al., 2016; Andrews & Westerman, 2012; Cantin et al., 2009; Eudave et al., 2018; Liu & Ou, 2011; Michaels et al., 2017; Park et al., 2011; Son et al., 2011; Wechsler et al., 2018). Older drivers also experienced more crashes than younger drivers during simulated driving (Belanger et al., 2015; Belanger et al., 2010; Michaels et al., 2017; Park et al., 2011). Finally, older drivers demonstrated poorer lane keeping behavior, with larger variability in lane position or deviation from the road, compared to younger drivers (Bunce et al., 2012; Chen et al., 2013; Eudave et al., 2018; Fofanova & Vollrath, 2011; Karthaus et al., 2018b; Ledger et al., 2019; Liu & Ou, 2011; Rodrick et al., 2013; Son et al., 2011; Wechsler et al., 2018). More information on the used driving simulator protocols and driving variables can be found in the supplementary tables 4-6.

3.3 Impact of cognitive function on driving performance

Cognitive function was assessed using various neuropsychological tests in 11 studies (Alonso et al., 2016; Andrews & Westerman, 2012; Belanger et al., 2015; Belanger et al., 2010; Bunce et al., 2012; Chen et al., 2013; Eudave et al., 2018; Ledger et al., 2019; Michaels et al., 2017; Park et al., 2011; Stinchcombe et al., 2011). According to the classification of Lezak et al. (2012) and Strauss et al. (2006), the neuropsychological tests were classified into 6 cognitive domains (Lezak et al., 2012; Strauss et al., 2006). The cognitive domains were general cognition, executive function, attention, processing speed, visuospatial perception, and memory. Table 4 illustrates the classification of each test into its cognitive domain.

General cognitive functioning

- Cognitive-Perceptual Assessment for Driving
- Mini-Mental State Examination
- National Adult Reading Test

Executive function

- Diagramming Relationships Test
- Digit Span
- Dual task: Timed Up and Go Test + Cognitive task
- Flanker Task
- Go/No Go task
- Rey Complex Figure Test - Organization
- Simple Visual Search
- Stroop Arrow Test
- Stroop Colour Word Test
- Task Switching
- Trail Making Test - B
- Verbal Fluency Test
- Wisconsin Card Sorting Test
- Zoo Map test

Attention

Selective:
- Trail Making Test – A
- Useful Field of View Test 3

Divided:
- Useful Field of View Test 2

Sustained:
- Digit Symbol Coding Test

Processing speed

- (2- and 4-) Choice Reaction Time
- Simple Reaction Time

Visuospatial perception

- 3-D Multiple Object-Tracking task
- Block Design Test
- Paper Folding Test
- Rey Complex Figure Test – Copy

Memory

- Immediate & delayed word recognition
- Rey Auditory Verbal Learning Test
- Rey Complex Figure Test – Immediate Recall
- Wechsler Memory Scale

Table 4: Classification of neuropsychological assessment

General cognition, executive function, and attention were evaluated most across the included studies (see Table 5 & 6). Overall, older persons performed worse than younger persons on various cognitive tests: (i) general cognition (Chen et al., 2013; Park et al., 2011), (ii) executive function (Alonso et al., 2016; Andrews & Westerman, 2012; Bunce et al., 2012; Chen et al., 2013; Eudave et al., 2018; Ledger et al., 2019; Stinchcombe et al., 2011), (iii) attention (Andrews & Westerman, 2012; Eudave et al., 2018; Ledger et al., 2019; Stinchcombe et al., 2011), (iv) processing speed (Andrews & Westerman, 2012; Bunce et al., 2012; Stinchcombe et al., 2011), (v) visuospatial perception (Andrews & Westerman, 2012), and (vi) memory (Bunce et al., 2012; Eudave et al., 2018; Ledger et al., 2019).

	Studies	Performance	Association with driving
General cognition	Alonso et al. (2016)	NS	Braking RT (Y & O)
	Andrews & Westerman (2012)	NS	**Lane keeping (O)**
	Belanger et al. (2010)	NR	NR
	Bunce et al. (2012)	O > Y	Lane keeping & car-following (Y & O)
	Chen et al. (2013)	Y > O	NR
	Ledger et al. (2019)	NS	Overall driving & Less speeding (Y)
	Michaels et al. (2017)	NR	NR
	Park et al. (2011)	Y > O	Crash, safer driving (Y & O)
	Stinchcombe et al. (2011)	NR	NR
Executive function	Alonso et al. (2016)	Y > O	Braking RT (Y & O)
	Andrews & Westerman (2012)	Y > O	Car following (anticipation) (Y & O)
	Belanger et al. (2015)	NR	**Crash (O)**
	Bunce et al. (2012)	Y > O	Lane keeping & car-following (Y & O)
	Chen et al. (2013)	Y > O	Left turning (Y & O)
	Eudave et al (2018)	Y > O	Higher speed (Y)
	Ledger et al. (2019)	Y > O	Lane keeping (Y & O)
	Park et al. (2011)	NR	Crash, safer driving (Y & O)
	Stinchcombe et al. (2011)	Y > O	Driving errors (Y & O)
Attention	Andrews & Westerman (2012)	Y > O	**Anticipation car-following (O),** lane keeping (Y), car-following (Y & O)
	Belanger et al. (2010)	NR	Crash (Y & O)
	Belanger et al. (2015)	NR	Crash (Y & O)
	Eudave et al (2018)	Y > O	Higher speed (Y)
	Ledger et al. (2019)	Y > O	NS
	Park et al. (2011)	NR	Crash, safer driving (Y & O)
	Stinchcombe et al. (2011)	Y > O	**Overall driving (O)**
Processing speed	Andrews & Westerman (2012)	Y > O	Lane keeping & speed consistency (Y & O)
	Belanger et al. (2010)	NR	NR
	Belanger et al. (2015)	NR	**Crash (O)**
	Bunce et al. (2012)	Y > O	Lane keeping & car-following (Y & O)
	Stinchcombe et al. (2011)	Y > O	Overall driving (Y)
Visuospatial perception	Andrews & Westerman (2012)	Y > O	Lane keeping (Y & O)
	Eudave et al (2018)	NS	Higher speed (Y)
	Ledger et al. (2019)	NS	Overall driving (Y & O), **less speeding (O)**
	Michaels et al. (2017)	NR	Crash, speed, lane keeping (Y & O)
Memory	Bunce et al. (2012)	Y > O	Lane keeping & car-following (Y & O)
	Eudave et al (2018)	Y > O	Higher speed (Y)
	Ledger et al. (2019)	Y > O	Overall driving (Y)

Table 5: Overview of association between cognitive function and driving
All associations presented in this table indicate that better performance on a neuropsychological test was related

to better driving behavior; Y: Younger persons, O: Older persons, NS: Not Significant, NR: Not Reported, in bold: associations specific for older drivers

3.3.1 General cognition

For both younger and older adults, better general cognitive function was related to better driving simulator performance, more specifically: a decreased braking reaction time (Alonso et al., 2016), increased lane keeping control (Bunce et al., 2012), less headway variability, i.e. the variability in distance or time from the car ahead when following a lead car (Bunce et al., 2012), lower crash rate, and safer steering, vehicle positioning and lane changing behavior (Park et al., 2011). Andrews and Westerman (2012) found that only for older adults, high ability on the National Adult Reading Test (NART) was associated with less variable lane keeping control (Andrews & Westerman, 2012). Ledger et al. (2019), on the other hand, found that, only for the young participants, better performance on the Mini-Mental State Examination (MMSE) was associated with less speeding behavior and a better overall driving score (Ledger et al., 2019).

3.3.2 Executive function

All of the included studies assessing executive function found significant associations with driving performance tests (Alonso et al., 2016; Andrews & Westerman, 2012; Belanger et al., 2015; Bunce et al., 2012; Chen et al., 2013; Eudave et al., 2018; Ledger et al., 2019; Park et al., 2011; Stinchcombe et al., 2011). Better performance on tests of executive function was associated with better driving performance in both young and older persons. Test performance had a positive impact on braking reaction time (Alonso et al., 2016), anticipation while driving (Andrews & Westerman, 2012), lane keeping control (Bunce et al., 2012; Ledger et al., 2019), headway variability during car-following (Bunce et al., 2012), gap size acceptance when turning left (Chen et al., 2013), crash rate (Park et al., 2011), speed control (Park et al., 2011), steering (Park et al., 2011), lane changes (Park et al., 2011), and driving errors (Stinchcombe et al., 2011). One study found that better executive function was associated with faster driving, but only in younger adults (Eudave et al., 2018). Another study found that older persons who experienced a crash during simulated driving had poorer executive function, and that crash rate decreased with better executive function (Belanger et al., 2015).

3.3.3 Attention

Better performance on **selective attention** tests of young and older persons was related to better driving performance: better car-following behavior with shorter headway adaption (Andrews & Westerman, 2012), lower crash rate (Belanger et al., 2015; Belanger et al., 2010; Park et al., 2011), safer lane changing and vehicle positioning (Park et al., 2011), and finally, a better overall driving score (Stinchcombe et al., 2011). Only for older adults, higher ability on selective attention was associated with better anticipation during a car-following task, while higher ability on selective attention in younger adults, was associated with lane keeping ability (Andrews & Westerman, 2012). For both young and older adults, better **divided attention** was associated with lower crash rate (Belanger et al., 2015; Belanger et al., 2010; Park et al., 2011), safer speed control (Park et al., 2011), steering (Park et al., 2011), lane changing (Park et al., 2011) and vehicle positioning (Park et al., 2011). In the study of Stinchcombe et al. (2011), there was an association between divided attention and a better overall driving score in only older adults (Stinchcombe et al., 2011). Better performance on **sustained attention** was associated with safer speed control, and lane changing (Park et al., 2011) for both young and older adults. Driving at a higher speed was associated with better sustained attention in a younger age group but not in an older population (Eudave et al., 2018).

3.3.4 Processing speed

For younger and older persons, faster processing speed was associated with better lane keeping (Andrews & Westerman, 2012; Bunce et al., 2012), driving at a more consistent speed (Andrews & Westerman, 2012), and better car-following behavior (Bunce et al., 2012). Stinchcombe et al. (2011) found that there was an association with better overall driving performance only for younger and middle-aged drivers (Stinchcombe et al., 2011). Older persons who crashed while driving had significantly slower reaction times than older persons who did not crash (Belanger et al., 2015).

3.3.5 Visuospatial perception

Better results on visuospatial perception tests were related to better lane keeping (Andrews & Westerman, 2012; Michaels et al., 2017), safer overall driving performance (Ledger et al., 2019), less crashes, and driving at a higher mean speed (Michaels et al., 2017) in both older and younger persons. However, Eudave et al. (2018) found that only for younger adult drivers, better visuospatial abilities were associated with driving at a higher mean speed, still under the imposed speed limit, than older adults (Eudave et al., 2018). Additionally, Ledger et al. (2019) found that only for older persons, better perception was related to less excessive speeding during simulated driving (Ledger et al., 2019).

3.3.6 Memory

Bunce et al. (2012) found that better memory function was related to better car-following behavior and better lane keeping behavior for older and younger persons (Bunce et al., 2012). Eudave et al. (2018) reported that driving at a higher speed was associated with better performance on memory tests, but only in younger persons (Eudave et al., 2018). Ledger et al. (2019) also found an association with visuospatial memory only in young persons, but for an overall driving score (Ledger et al., 2019).

	n	Mean age (yrs)	Cognitive Tests	Association Driving & Cognition: O & Y	Association Driving & Cognition: O	Association Driving & Cognition: Y
Alonso et al., 2016	**O** n=102 **Y** n=62	**O** 70.4 (5.8) **Y** 39.8 (7.2)	MMSE DT	MMSE, DT ↑ ⇒ braking RT ↓	/	/
Andrews & Westerman, 2012	**O** n=22 **Y** n=22	**O** 66.77 (5.07) **Y** 33.32 (4.37)	NART TMT A DRT TSW CRT PFT	CRT, TMT A, PFT ↑ ⇒ Car-following ↑ NART, PFT, CRT, TMT A ↑ ⇒ Lane keeping ↑ CRT ↑ ⇒ Speed variability ↓ TSW, TMT A ↑ ⇒ Anticipation car-following ↑	TMT A ↑ ⇒ Anticipation car-following ↑ NART, CRT ↑ ⇒ Lane keeping ↑	PFT, CRT, TMT A ↑ ⇒ Lane keeping ↑
Belanger et al., 2010	**O** n=20 **Y** n=20	**O** 73.4 (5.17) **Y** 29.5 (4.32)	MMSE UFOV SRT CRT	UFOV: no crash > crash	UFOV 2&3: no crash > crash	/
Belanger et al., 2015	**O** n=35 **Y** n=35	**O** 72.1 (4.34) **Y** 28.9 (3.96)	UFOV TMT SRT CRT	/	CRT, TMT B, UFOV 2&3: no crash > crash UFOV 2&3, TMT B ↑ ⇒ Crash ↓	/
Bunce et al., 2012	**O** n=21 **Y** n=24	**O** 71.24 (6.83) **Y** 21.29 (1.71)	NART SVS Flanker SCWT SAT CRT WR	CRT, SVS, SCWT, SAT, WR ↑ ⇒ Car-following ↑ CRT, Flanker, SAT, WR ↑ ⇒ Lane keeping ↑	/	/
Chen et al., 2013	**O** n=13 **Y** n=16	**O** 77.62 (4.86) **Y** 46.13 (5.41)	MMSE WCST TMT B	WCST ↑ ⇒ Left turn ↑	/	/
Eudave et al., 2018	**O** n=20 **Y** n=22	**O** 67.4 (5.2) **Y** 30.3 (4.3)	DSCT TMT ZMT SCWT DS RAVLT WMS BDT	/	/	TMT B, ZMT, SCWT, DS, DSCT, BDT, WMS ↑ ⇒ Speed ↑

Ledger et al., 2019	**O** n=43 **Y** n=51	**O** 66.77 (5.07) **Y** 33.32 (4.37)	MMSE TMT RCFTO RCFTR RCFTC	**/**	RCFTC ↑ ⇒ Speeding ↓ RCFTO ↑ ⇒ Lane keeping ↑ RCFTC & TMT B ↑ ⇒ Driving score ↑	MMSE ↑ ⇒ Speeding ↓ RCFTO ↑ ⇒ Lane keeping ↑ RFCTR, RCFTC & MMSE↑ ⇒ Driving score ↑
Michaels et al., 2017	**O** n=51 **M-A** n=35 **Y** n=29	**O** 77.2 (5.01) **M-A** 36 (8.68) **Y** 20.15 (1.19)	MMSE 3D-MOT	3D-MOT ↑ ⇒ Crash ↓, Lane keeping ↑, Speed ↑	**/**	**/**
Park et al., 2011	**O** n=55 **Y** n=48	**O** 69.91 (3.63) **Y** 34.25 (3.62)	CPAD: Attention TMT SCWT DS	CPAD fail ⇒ Crash, Steering, Vehicle position, Lane change ↑ Attention, SCWT, DS, TMT A&B ↑ ⇒ Crash ↓ Attention, DS ↑ ⇒ Speed control ↑ Attention, SCWT, DS ↑ ⇒ Steering ↑ Attention, TMT A ↑ ⇒ Vehicle position ↑ Attention, SCWT, DS, TMT A&B↑ ⇒ Lane change ↑	**/**	**/**
Stinchcombe et al., 2011	**O** n=23 **M-A** n=30 **Y** n=56	**O** 69.9 **M-A** 29.6 **Y** 18.5	MMSE UFOV TMT SRT CRT	TMT A&B, SRT, CRT, UFOV ↑ ⇒ Driving demerit points ↓, Simulator errors ↓	UFOV 2 ↑ ⇒ Driving demerit points ↓	NS

Table 6: Overview of cognitive functioning and driving performance

Only statistically significant results ($p<0.05$) are presented in the table. O: Older, Y: Younger, M-A: Middle-Aged, NS: Not Significant, NR: Not Reported; Cognitive tests: MMSE: Mini-Mental State Examination, DT: Dual Task Test, NART: National Adult Reading Test, TMT: Trail Making Test, DRT: Diagramming Relationships Test, TSW: Task Switching, CRT: Choice Reaction Time, WR: Word Recognition, PFT: Paper Folding Test, UFOV: Useful Field of View test, SRT: Single Reaction Time, SVS: Simple Visual Search, ZMT: Zoo Map Test, SCWT: Stroop Color Word Test, SAT: Stroop Arrow Test, DS: Digit Span, WCST: Wisconsin Card Sorting Test, RT: Reaction Time, DSCT: Digit Symbol Coding Test, RAVLT: Rey Auditory Verbal Learning Test, WMS: Wechsler Memory Scale, BDT: Block Design Test, RCFTO: Rey Complex Figure Test - Organization, RCFTR: Rey Complex Figure Test – Immediate Recall, RCFTC: Rey Complex Figure Test - Copy, 3D-MOT: 3-dimensional Multiple Object-Tracking task, CPAD: Cognitive-Perceptual Assessment for Driving

3.4 Dual task performance and driving

Dual tasking during simulated driving was evaluated in 11 studies (see Table 7) (Belanger et al., 2010; Cantin et al., 2009; Fofanova & Vollrath, 2011; Karthaus et al., 2018a; Liu & Ou, 2011; Perlman et al., 2019; Pitts & Sarter, 2018; Rodrick et al., 2013; Son et al., 2011; Stinchcombe et al., 2011; Wechsler et al., 2018). The dual task consisted of driving in the simulator and concurrently performing a secondary task, such as a reaction time task or a functional task like using a navigation system. Dual tasking had a detrimental effect on secondary task performance for both younger and older persons, with slower reaction times and poorer accuracy. However, this effect was more pronounced for older than for younger persons (Cantin et al., 2009; Karthaus et al., 2018a; Perlman et al., 2019; Pitts & Sarter, 2018; Rodrick et al., 2013; Son et al., 2011; Stinchcombe et al., 2011; Wechsler et al., 2018).

Regarding the driving task, dual tasking also had a detrimental effect on various driving parameters for both young and older adults. For instance, lane keeping control and steering behavior were poorer while dual tasking (Fofanova & Vollrath, 2011; Liu & Ou, 2011; Perlman et al., 2019; Son et al., 2011). Furthermore, young and older persons drove at a slower and more inconsistent speed when performing a secondary task (Liu & Ou, 2011; Son et al., 2011; Wechsler et al., 2018). The detrimental effect of dual tasking was more prominent in older subjects in almost all of the studies reporting this detrimental effect: poorer lane keeping and steering (Fofanova & Vollrath, 2011; Perlman et al., 2019; Pitts & Sarter, 2018; Son et al., 2011; Wechsler et al., 2018), and driving at a more inconsistent speed (Son et al., 2011). Finally, Belanger et al. (2010) found that older and younger subjects who crashed while driving, had slower reaction times and poorer accuracy on the secondary task when performing the two tasks simultaneously, than those who did not crash, with the older drivers experiencing significantly more crashes (Belanger et al., 2010).

	n	Mean age (yrs)	Secondary Task	Dual Task performance: Secondary Task	Dual Task performance: Driving Task
Belanger et al., 2010	**O** n=20 **Y** n=20	**O** 73.4 (5.17) **Y** 29.5 (4.32)	Divided Attention Task	RT: crash > no crash (O & Y) Accuracy: no crash > crash (O & Y)	NR
Cantin et al., 2009	**O** n=10 **Y** n=10	**O** 68.4 (3.0) **Y** 24.0 (3.5)	RT Task	**RT**: complex driving DT > simple driving DT > ST, for complex driving: RT ↑ **(O > Y)** **Accuracy:** ST > simple driving DT > complex driving DT (O & Y), **(Y > O)**	NR
Fofanova & Vollrath, 2011	**O** n=10 **Y** n=10	**O** 68.4 (4.2) **Y** 38.6 (4.0)	D2 Test of Attention	RT: DT > ST (O & Y) Accuracy: ST > DT (O & Y) **Number of items**: ST > DT, **Y > O** (ST & DT)	Lane keeping: ST > DT (O & Y) **Lane keeping variability: DT > ST (O)** RT Lane Change: DT > ST (O & Y)
Karthaus et al., 2018b	**O** n=20 **Y** n=20	**O** 59.6 (3.2) **Y** 22.9 (1.8)	Brake RT task + distracting stimuli (visual or auditory)	NR	**Braking RT:** Y: ST > auditory & visual DT; **O**: visual DT > ST > auditory DT **Braking accuracy**: visual DT: **Y > O**
Liu & Ou, 2011	**O** n=24 **Y** n=24	**O** 69.21 (3.05) **Y** 23.10 (1.54)	Divided Attention Task + Handsfree phone calling	RT: simple & complex DT > ST (O & Y) Accuracy: ST > simple DT > complex DT (O & Y)	Lane keeping: ST > simple & complex DT (O & Y) Speed variability: ST & complex DT > simple DT (O & Y) Speed mean: ST & simple DT > complex DT (O & Y)
Perlman et al., 2019	**O** n=18 **Y** n=18	**O** 62.0 (4.1) **Y** 25.3 (2.5)	Detection Response Task + phone or smartwatch	**RT**: phone & smartwatch DT > ST **(O > Y)** **Accuracy**: ST > smartwatch DT > phone DT **(Y > O)**	Lane keeping variability: phone DT > smartwatch DT & ST (O & Y) **Steering**: phone DT > smartwatch DT > ST **(O > Y)**
Pitts & Sarter, 2018	**O** W: n=12 R: n=12 **Y** n=12	**O** W: 68.16 (3.76) R: 68.33 (2.20) **Y** 22.67 (2.71)	Stimulus Detection task	**RT**: DT > ST, **O > Y** **Accuracy in DT**: **Y > O**	**Lane keeping** change after stimuli: **O > Y**
Rodrick et al., 2013	**O** n=8 **M-A** n=8 **Y** n=8	NR	Secondary task: Tracking, Visual Search, Memory, Navigation	**Tracking in DT**: **Y > O** **Visual search in DT**: **Y > O**	Lane keeping: Memory DT & ST > Tracking DT > Visual search DT > Navigation DT (O & Y)

Son et al., 2011	**O** n=29 **Y** n=32	**O** 64.55 (2.81) **Y** 25.28 (2.02)	n-Back task	**Accuracy:** ST > DT **(O > Y)**	Speed mean: ST > DT (Y & O) **Speed variability**: DT > ST **(O only)** **Lane keeping variability**: ST > DT **(O > Y)** Steering reversal rate: DT > ST (O & Y)
Stinchcombe et al., 2011	**O** n=23 **M-A** n=30 **Y** n=56	**O** 69.9 **M-A** 29.6 **Y** 18.5	Divided Attention Task	RT difference scores from baseline: **Straight roads**: O > Y **Intersections**: O > Y (right & no turn, NOT for left turn) **Lane change**: O > Y	NR
Wechsler et al., 2018	**O** n=61 **Y** n=63	**O** 69.97 (2.69) **Y** 23.17 (2.83)	Secondary task: Typing, Reasoning, Memory	**RT**: DT > ST **(O)** **Accuracy**: ST > DT **(O)**	Speed mean: ST > DT (O & Y) Speed variability: DT > ST (O & Y) **Lane keeping mean**: DT more lateral position > ST **(O > Y)** **Lane keeping variability**: DT > ST **(O > Y)**

Table 7: Overview of dual tasking and driving performance

*Only statistically significant results (p<0.05) are presented in the table. This table indicates the dual task cost on secondary task and driving performance, and to which age group this corresponds. For example, for the study of Cantin et al. (2009) indicates that the reaction time for the secondary task performance is higher when dual tasking, and this effect is bigger in older persons. O: Older, Y: Younger, M-A: Middle-Aged, W: Working, R: Retired, RT: Reaction Time, DT: Dual task, ST: Single Task, NS: Not Significant, NR: Not Reported, in **bold**: specific for older drivers*

3.5 Neural correlates of driving

Four studies assessed the brain dynamics related to driving performance of older compared to younger persons (see Table 8) (Eudave et al., 2018; Getzmann et al., 2018; Karthaus et al., 2018a, 2018b). The study of Eudave et al. (2018) examined the neural correlates of a visuospatial perception task using functional Magnetic Resonance Imaging (fMRI) and its association to driving simulator performance. Younger persons performed significantly better than older persons, whereby deterioration in performance of older persons was associated with a widespread hyperactivity in basal ganglia, and frontoparietal and cerebellar regions, and a decreased functional connectivity between default-mode network zones. During the simulated drive, younger persons drove at a higher speed than older persons, which was associated with greater activation and connectivity of the default-mode network during the perception task, and with better executive function as evaluated by neuropsychological tests (Eudave et al., 2018).

One research group published 3 studies using electroencephalography (EEG) to study the underlying neurophysiological processes related to simulated driving performance of older and younger persons (Getzmann et al., 2018; Karthaus et al., 2018a, 2018b). Getzmann et al. (2018) reported that even though older and younger persons did not differ in lane keeping control, differences in EEG measures were found. It was found that Alpha power[1] increased with less demanding driving situations only in the younger group, while only in the older group an increase in Theta power[1] was related to lower steering variability (Getzmann et al., 2018). Another study that evaluated lane keeping performance did find differences in driving performance between a younger and older age group (Karthaus et al., 2018b). The older persons could be divided into 2 groups according to the driving performance: a group with high lane keeping variability and a group with low variability. The lane keeping performance of the low variability group did not differ from performance of the younger comparison group. Differences in EEG measures were again found between the young and older persons, and between the two older persons groups. Theta power was stronger for younger than for the older persons of the low variability group, although lane keeping performance was similar between both groups. Regarding the two older persons groups, Theta and Alpha power was stronger in the group with high lane variability than in the group with low variability (Karthaus et al., 2018b).

Finally, the neural correlates of dual tasking while driving were analyzed, using a braking reaction time task. It was found that older persons' braking performance was less accurate and slower when additional distracting visual stimuli were presented simultaneously with the brake light. This was associated with a smaller ERP amplitude and later onset latency (posterior P3b ERP) for the

[1] With EEG, neural oscillations are measured. These oscillations can be characterized by their frequency and are divided into different frequency bands, such as Alpha and Theta. An increase of power in the Alpha frequency band has been previously associated with attentional disengagement (Klimesch, 2012), while Theta power has been associated with processes of cognitive control (Cavanagh & Frank, 2014).

combination of the braking light stimulus and the visual stimulus in older persons (Karthaus et al., 2018a).

	n	**Mean age** (yrs)	**Neuroimaging**	**Driving & neuroimaging results: O & Y**	**Driving & neuroimaging results: O**	**Driving & neuroimaging results: Y**
Eudave et al., 2018	**O** n=20 **Y** n=22	**O** 67.4 (5.2) **Y** 30.3 (4.3)	**fMRI:** Brain activity & Functional connectivity analysis during HSD Task	/	**Activity:** ↑ frontoparietal, basal ganglia & cerebellar **Connectivity**: ↑ between frontal, parietal and basal regions **Association with driving**: NS	**Connectivity**: ↑ between DMN areas **Association with driving**: Driving speed & proper DMN dynamics
Getzmann et al., 2018	**O** n=16 **Y** n=16	**O** 63.3 **Y** 24.1	**EEG:** Relative Theta & Alpha power (anterior & posterior)	**Theta:** Y > O ↓ with ↑ Time on Task ↑ with ↑ Task Load **Alpha:** ↑ with ↑ Time on Task	**Theta:** ↑ ⇒ Steering variability ↓ **Alpha:** ↑ with ↑ Task Load	**Alpha:** ↑ over time with ↓ Task load
Karthaus et al., 2018a	**O** n=20 **Y** n=20	**O** 59.6 (3.2) **Y** 22.9 (1.8)	**ERP:** P2 (fronto-central) & P3b (posterior)	**P3b:** Amplitude: Y > O Latency: DT > ST (O > Y) **P2:** Amplitude: Y > O	**P3b:** Amplitude: ST > DT Amplitude ↓ ⇒ Braking RT ↑ & accuracy ↓ **P2:** Latency: DT > ST	**/**
Karthaus et al., 2018b	**O** High: n=14 Low: n=14 **Y** n=14	**O:** High: 65.4 (2.2) Low: 63.9 (3.9) **Y** 25.1 (2.7)	**EEG**: Theta, Alpha and Beta power (fronto-central & posterior)	**Alpha:** O-High > O-Low **Theta:** Y > O-Low O-High > O-Low	**Alpha, Theta & Beta:** ↓ with ↑ complex driving **O-High vs O-Low:** O-High: Lane keeping variability ↑ ⇒ Theta, Alpha ↑ O-Low: Lane keeping variability ↓ ⇒ Theta, Alpha ↓	**/**

Table 8: Overview of neuroimaging and driving performance

Only statistically significant results ($p<0.05$) are presented in the table. O: Older, Y: Younger, RT: Reaction Time, HSD: High Speed Discrimination task, DMN: Default Mode Network, ST: Single Task, DT: Dual Task, ERP: Event-Related Potential, NS: Not Significant, NR: Not Reported

4 Discussion

This systematic review aimed to provide a detailed overview of the literature concerning the impact of age-related changes in cognitive function on driving performance to help identify the physiological and functional biomarkers that can be used to design remedial measures to preserve or improve safe driving behavior. Yet, the studies included in this review demonstrate a large variety in driving outcome measures, and also in cognitive outcome measures. This heterogeneity required the division of cognitive and driving measures into domains and subgroups to be able to draw conclusions.

Overall, all domains of cognitive function were found to be associated with the driving outcomes to some extent, irrespective of age. This signifies that higher cognitive ability is associated with better driving performance. This review found some evidence that poorer cognitive function of both younger and older adults, across all of the included cognitive domains, related to more inconsistent driving behavior (Andrews & Westerman, 2012; Bunce et al., 2012; Michaels et al., 2017; Park et al., 2011). Nevertheless, older persons most often performed worse on both cognitive and driving outcomes in comparison to the younger adult persons. This was also found for dual task performance in the driving simulator: the consistency in driving performance was negatively affected by an additional task in both younger and older persons (Fofanova & Vollrath, 2011; Perlman et al., 2019; Pitts & Sarter, 2018; Rodrick et al., 2013; Son et al., 2011; Wechsler et al., 2018), yet this effect was generally larger for older persons, due to the higher dual task cost while driving (Fofanova & Vollrath, 2011; Pitts & Sarter, 2018; Son et al., 2011; Wechsler et al., 2018).

Below, we will discuss the following in more detail. First, we will give an overview of the general driving behavior of older adults as compared to younger adults. Then, we will discuss the impact of cognition and dual tasking on driving performance based on neuropsychological tests, followed by the neurophysiological findings that are related to driving performance. Finally, we will address the implications and limitations of this systematic review.

4.1 Age-related changes in driving performance

As compared to younger adult drivers, older persons drove at a slower speed in a similar driving context. This is in accordance with other literature that has found that older persons may adapt their driving speed as compensation to reduce task demands, especially in more complex driving situations and/or dual task driving protocols (Charlton et al., 2013; Cuenen et al., 2015; Doroudgar et al., 2017; Ebnali et al., 2016). This tendency to reduce driving speed could indicate a more defensive driving strategy in order to anticipate and cope with more challenging driving events. The older drivers also demonstrated a more inconsistent driving pattern than the younger comparison groups. Older persons had higher variability in speed, were less consistently in car-following situations and in lane keeping behavior. Inconsistency in driving performance, and more specifically lateral control, could indicate driving impairment due to a higher task demand (Cuenen et al., 2015). This more inconsistent driving pattern could be the result of age-related changes in cognitive function (Young & Bunce, 2011).

4.2 Impact of cognition and dual tasking performance on driving performance

General cognitive function was evaluated the most across all of the included studies, together with executive function. With respect to general cognitive functioning, no conclusive evidence was found for an age-related deterioration, with only 2 out of 9 studies reporting that younger persons performed better than older persons (Chen et al., 2013; Park et al., 2011). This might seem surprising, since an abundance of research has demonstrated a negative influence of aging on general cognitive functions (Salthouse, 2012). However, a distinction between two types of cognition can be made, i.e. crystallized and fluid ability (Harada et al., 2013). Crystallized abilities refer to skills or knowledge that are acquired across the lifespan, and thus increase with higher age. Fluid cognition reflects abilities such as novel problem-solving and reasoning, which tend to deteriorate starting at about age 30 (Salthouse, 2012). In this review, both fluid and crystallized cognition were taken into account for assessing general cognition, which might explain why general cognition in older adults was preserved.

Only 2 studies found age-dependent associations with driving performance measures, with more consistent lane keeping being associated with better cognitive function in older adults (Andrews & Westerman, 2012), and overall driving performance with better cognitive function in the younger adults (Ledger et al., 2019). This association in only younger persons seems counterintuitive; however, this could be due to the use of the MMSE, a tool used to screen for cognitive impairment and dementia. All of the participants had normal scores, and since the MMSE is not meant to discriminate between high performing individuals, the results might not be suitable to interpret (Creavin et al., 2016; Tombaugh & McIntyre, 1992). Although Mathias and Lucas (2009) found that the MMSE was predictive for simulator driving in older adults, other research has demonstrated that the association between MMSE and on-road driving performance is rather poor (Wagner et al., 2011).

Executive function and attention were frequently measured cognitive domains across the included studies as well. These two aspects of cognition also seem to be highly associated with driving performance, by associations with measures such as crash rate and lane keeping consistency. Furthermore, almost all of these studies reported that older persons performed significantly worse than younger persons on executive function, and found evidence that selective attention is subject to age-related decline. Therefore, adequate executive function and complex attention abilities seem to be essential for driving performance, irrespective of age. However, as we see that these cognitive functions deteriorate with increasing age, corroborated by the findings in other research on age-related deterioration in executive function and complex attention (Harada et al., 2013; Kirova et al., 2015; Salthouse, 2010), older persons' driving skills will presumably suffer more than that of younger persons. Indeed, previous literature with older drivers has reported that neuropsychological tests of executive function and attention are also associated with other driving outcome measures than simulated driving, such as on-road driving and crash risk. It has been found that executive function impairment may reduce driving safety based on crash records, on-road or simulated driving (Anstey & Wood, 2011; Anstey et al., 2005; Asimakopulos et al., 2012; Mathias & Lucas, 2009). More specifically, the Useful Field of View (UFOV) test of attention, has been demonstrated to be sensitive for detecting blind-spot errors and to be predictive of driving performance measured by on-road tests, simulator tests and documented driving problems (Anstey & Wood, 2011; Anstey et al., 2005; Mathias & Lucas, 2009). Additionally, Cuenen et al. (2015) found that higher attention abilities in older drivers was associated with lower crash occurrence, and had a moderating effect on lane keeping while performing a dual task (Cuenen et al., 2015).

Tests of the remaining 3 cognitive domains, i.e. processing speed, visuospatial perception, and memory were least included across studies. The included studies indicated that memory and processing speed were found to deteriorate with age, which has also been demonstrated in other aging research studies (Harada et al., 2013; Salthouse, 2010). Nevertheless, no clear deterioration in visuospatial perception was found, with only one study reporting better scores in younger adult persons (Andrews & Westerman, 2012), even though this has been found to deteriorate in cognitive aging research (Harada et al., 2013). For these 3 cognitive domains, there was an association with overall driving and with specific driving measures such as speed consistency, lane keeping, and car-following behavior in both younger and older adults, for which better cognitive performance was related to better driving performance (Andrews & Westerman, 2012; Bunce et al., 2012; Ledger et al., 2019; Michaels et al., 2017). In the older population, better visuospatial perception was associated with less speeding behavior (Ledger et al., 2019), and an inter-individual variability was found, with older drivers who crashed having a significantly slower processing speed than those who did not crash (Belanger et al., 2015). These results are in line with the review of Anstey et al. (2005), which also found associations between memory, processing speed and visuospatial perception and on-road driving assessment (Anstey et al., 2005).

Finally, studies indicated that both young and older drivers tend to slow down and drive less consistently when distracted during the performance of a dual task. However, the impact of distractions on driving performance was larger in the older population (Fofanova & Vollrath, 2011; Perlman et al., 2019; Pitts & Sarter, 2018; Son et al., 2011; Wechsler et al., 2018). The performance on the secondary task also deteriorated in comparison to baseline performance in the older population while driving, more than compared to younger adults (Cantin et al., 2009; Karthaus et al., 2018a; Perlman et al., 2019; Pitts & Sarter, 2018; Rodrick et al., 2013; Son et al., 2011; Stinchcombe et al., 2011; Wechsler et al., 2018). An on-road driving study also found that older drivers had a less consistent driving speed when performing a demanding dual task (Ebnali et al., 2016). This difficulty to perform tasks simultaneously due to aging has also been demonstrated in other studies incorporating a motor task with a secondary task (Forte et al., 2019; Smith et al., 2017). Older persons could have less attentional resources available to be able to combine multiple tasks, or struggle with differentiating between relevant and irrelevant stimuli, and thereby overstraining those attentional resources (Hahn et al., 2010; McAlister & Schmitter-Edgecombe, 2013; Verhaeghen et al., 2003).

Additionally, literature has reported that the cognitive domains of executive function and complex attention are essential aspects of dual- and multitasking performance (MacPherson, 2018; Yogev-Seligmann et al., 2008). This might help explain the deterioration in older driver performance since the studies included in this review indicate an age-related decline in executive function and complex attention, and these domains were found to be associated with driving performance.

4.3 Neural correlates of driving in an older population

The above-mentioned changes in cognitive function of older persons can be due to age-related changes in the availability of neural resources, due to brain atrophy or changes in functional connectivity (Cabeza et al., 2018; Fjell et al., 2017; Reuter-Lorenz & Cappell, 2008; Spreng et al., 2010). Neurocognitive aging research has found that older adults exhibit a stronger and more extended brain activation in comparison to younger persons in a variety of cognitive tasks (Reuter-Lorenz & Cappell, 2008). Other research has found that during complex motor tasks, older persons show additional activation in regions related to cognitive monitoring, such as the prefrontal cortex, even when the behavioral performance is comparable in older and younger persons (Heuninckx et al., 2005). Hence, a shift from automatic processing to more cognitively controlled information processing is commonly observed (Heuninckx et al., 2005). This observed overactivation could serve as a compensatory mechanism for neurodegenerative processes and increased task demands in order to preserve the behavioral performance in older persons, acknowledged as the compensation hypothesis (Cabeza et al., 2018; Heuninckx et al., 2008; Reuter-Lorenz & Cappell, 2008).

The literature evaluating the underlying brain dynamics related to simulated driving in an aging population is rather sparse. Some of the neuroimaging studies found results that were in line with the compensation hypothesis. For instance, in less difficult driving situations, Alpha power increased only in the younger group, while no differences in driving performance between young and old were demonstrated (Getzmann et al., 2018). Since increased Alpha power has been demonstrated to indicate attentional disengagement or boredom (Borghini et al., 2014; Herrmann & Knight, 2001; Klimesch, 2012; Wascher et al., 2016), this lack of an increase in older drivers could signify that they required a higher attentional demand to maintain their performance on the driving task. Secondly, increased Theta power was associated with less steering variability only in older drivers (Getzmann et al., 2018). Since frontal Theta power has been associated with mental processes such as cognitive control and mental effort (Cavanagh & Frank, 2014), this could indicate that increased mental effort resulted in a more adequate steering behavior. As this association was only found for the older persons, this could also be an indication of the compensation hypothesis (Cabeza et al., 2018; Heuninckx et al., 2008; Reuter-Lorenz & Cappell, 2008), with older drivers experiencing higher task demands and requiring more cognitive control to keep the car in the center of the driving lane, at a similar level as the younger persons.

However, this brain overactivation may also be due to an age-related reduction in the concentration of the inhibitory neurotransmitter gamma-aminobutyric acid (GABA) (Cassady et al., 2019; Koen et al., 2020). This loss could lead to a non-functional spread of brain activity with no improvement or even a deterioration in behavioral performance, known as the dedifferentiation hypothesis (Heuninckx et al., 2008; Koen et al., 2020; Sala-Llonch et al., 2015). Some of the included studies point towards this dedifferentiation hypothesis, with differences in driving performance between young and old, or even between high and low performing older persons (Karthaus et al., 2018b). Alpha and Theta power was increased in the older persons who had a less consistent lane keeping performance as compared to the better performing older group, which could be an indication of dedifferentiation. This also indicates that the worse performing group required more mental effort, yet they were less attentive during the lane keeping task. This group, therefore, employed a more reactive driving strategy, in which they responded to the environmental information, while the better performing group employed a more alert and proactive driving strategy, in which they anticipated to the available information and actively used this to plan their driving behavior (Karthaus et al., 2018b). Additionally, the ERP study found that an increase in braking reaction time was associated with smaller P3b amplitude in the older adults (Karthaus et al., 2018a). Since the P3b is associated with cognitive control of attentional and stimulus evaluation processes (Polich, 2007), this could indicate that older adults have less neural resources at their disposal to manage the processing of a secondary stimulus (Gajewski & Falkenstein, 2014; Karthaus et al., 2018a). Finally, older persons performed worse than younger persons on a driving related visuospatial speed discrimination task, which was associated with widespread brain hyperactivity in the older persons, again supporting the dedifferentiation hypothesis (Eudave et al., 2018). Furthermore, driving at a higher mean speed was associated with efficient default-mode network activity and connectivity only in younger persons, while this association seemed to be lost in older persons. This network probably loses its efficiency in older persons due to reduced deactivation and weakened connectivity (Eudave et al., 2018; Reuter-Lorenz & Cappell, 2008). Therefore, this could indicate that the compensatory behavior of slower driving in older persons, to cope with the increased mental effort during challenging driving situations, might stem from age-related changes in the underlying brain dynamics (Eudave et al., 2018).

4.4 Towards preventive measures and rehabilitating techniques

In conclusion, cognitive performance tends to deteriorate with higher age, which might explain poorer driving performance in older adults, and thus possibly leading to a higher risk of accident involvement. Currently, available screening protocols seem to be insufficient to accurately predict driving performance due to the complexity of this skill. Moreover, mandatory driving cessation could lead to the use of higher risk mobility options (e.g. as pedestrians or cyclists), or impact the quality of life (Siren & Haustein, 2015). Therefore, we recommend complementing driving screening in the context of license renewal procedures, with the implementation of preventive or remedial measures and training strategies in order to preserve or improve safe driving in older persons.

This systematic review found that older persons drove less consistently than the younger adult drivers, and that they compensate for age-related cognitive decline by driving slower, in order to cope with larger task demands during driving. Therefore, at risk older drivers could benefit from strategies aimed at reducing driving task demands. For instance, guidelines regarding the driven vehicle could be formulated, such as recommending vehicles with automatic gear transmission or other technologies. Recent technological advances in the development of In-Vehicle Information Systems (IVIS), Advanced Driving Assistance Systems (ADAS), or, on an even higher level, the development of autonomous driving vehicles may increase driving safety in an older population (Classen et al., 2019; Knoefel et al., 2019). Driving problems such as poorer lane keeping or speed control that arise due to age-related changes in cognitive function, could be remedied by smart driver alerts or further automation of corrective steering, speeding or braking input. However, IVIS might not always be beneficial to older drivers. External alerts could be considered as a secondary task, and might initiate driving problems. Therefore, these alerts should be tailored to the older individual (Classen et al., 2019). Considering autonomous driving, various technical, legal or ethical challenges need to be taken into account. Additionally, it is required that older drivers specifically trust and learn to use these technologies, as they might be skeptical to hand over driving control (Knoefel et al., 2019).

Secondly, education programs could focus on informing older persons of these increased task demands, and how to reduce them by taking self-regulatory actions (Molnar & Eby, 2008). Older drivers could self-regulate their driving behavior by for instance avoiding distracting stimuli, such as handsfree calling or interacting with radio or GPS systems.

Finally, we recommend implementing individually tailored training protocols in order to increase safe driving behavior and reduce task demands. These could focus on increasing dual tasking abilities or on task specific training, using a driving simulator. Previous research has indicated that this approach using driving simulator training has the potential to enhance road driving performance in older persons (Casutt et al., 2014). Adding adjuvant non-invasive brain stimulation protocols could further support increasing cognitive resources in order to cope with larger task demands during driving. This could increase safe driving behavior in an older population, since research has found positive effects on both cognitive and motor functions in older adults (Perceval et al., 2016; Summers et al., 2016). A stimulation technique such as transcranial Direct Current Stimulation (tDCS) is portable, hence it is feasible to use in a daily life setting such as driving. Previous studies using tDCS while driving in a young population found promising results for improving car-following and lane keeping behavior, which might be relevant for older persons as well (Beeli et al., 2008; Sakai et al., 2014). Moreover, implementing these neuromodulation techniques could aid in exploring the causal role between a targeted brain region and their association with driving performance in an older population (Gomes-Osman et al., 2018; Woods et al., 2016). This can give more insight into the aging processes that play a role in driving ability, and help us identify the brain regions which need to be targeted with brain stimulation in order to improve driving performance in older persons.

4.5 Limitations

There are some limitations to this systematic review that may reduce the significance of our findings. First of all, due to the heterogeneity of the literature using different outcome measures and different protocols for evaluating cognition and driving performance, it was difficult to compare across studies and to draw clear and definite conclusions. This also made a meta-analysis impossible. Due to this heterogeneous literature, cognition was classified into domains. Although this classification was based on reliable literature, this remains a relatively arbitrary division (Lezak et al., 2012; Strauss et al., 2006). It is well known that some of the reported cognitive domains overlap with other domains, and therefore, a neuropsychological test could be considered part of more than one domain. For example, for the cognitive domain of divided attention, adequate switching and inhibition capacity is needed, which is also a component of executive function (Strauss et al., 2006). Likewise, there was methodological variability in the driving evaluation that required a division into subsets. Even though all included studies employed a simulated drive as driving outcome, there were variations in driving protocol and driving related measures (for an overview: see Supplementary Table 4-6). For example, some studies employed a more monotonous car-following or lane keeping task in which they were not required to operate the gas pedal for controlling driving speed (Getzmann et al., 2018; Karthaus et al., 2018a, 2018b), while other studies used a more realistic driving scenario requiring the participant to react adequately to challenging driving events such as intersections. These differences across studies complicate generalization over the different driving simulator tasks. In addition, the included studies integrated different motor and cognitive secondary tasks into the simulated drive, which might influence driving performance differently. However, when focusing on its impact on driving, each type of dual task can give us insight if driving ability, i.e. the extent of automatization, is affected.

Secondly, there were variations in the age range for the younger comparison groups. In 4 studies a young adult inexperienced population (younger than 25 years of age) was added as a comparison group, with two of them adding a more experienced younger person comparison group between the ages of 25 and 55 as well (Bunce et al., 2012; Ledger et al., 2019; Michaels et al., 2017; Stinchcombe et al., 2011). This younger and more inexperienced group is more likely to be involved in motor vehicle crashes than middle-aged adults (Keating & Halpern-Felsher, 2008). Not only a lack of driving experience might explain this higher crash incidence, but also underdeveloped executive function or cognitive control (Ross et al., 2015; Ross et al., 2016; Walshe et al., 2017). In adolescents, executive function is still developing parallel with the maturation of the frontal lobe, which is associated with increased risk-taking (Huizinga et al., 2006; Romer et al., 2011). The inclusion of these adolescent comparison groups might have given a distorted representation of the age-related changes in cognition that impact driving performance.

Additionally, the methodological quality of some of the included studies was rather poor, which makes it difficult to infer strong conclusions. Some of the included studies did not analyze or report the differences in cognition between the age groups, or did not even evaluate the association between cognition and driving for each of the age groups separately. Also, a minority of the included studies did not report if the participants were screened for mild cognitive impairment (Sanford, 2017), resulting in a poor quality rating (Chen et al., 2013; Park et al., 2011; Rodrick et al., 2013). However, none of the conclusions in this systematic review are based on only the studies that were of poor quality.

Moreover, only some studies incorporated multivariate analyses to control for multicollinearity between the cognitive variables (Eudave et al., 2018; Ledger et al., 2019). This hinders the isolation of exclusive associations between a variable of a certain cognitive domain and driving performance. The statistical methods used in several of the included studies did not allow such differentiation (Belanger et al., 2015; Belanger et al., 2010; Chen et al., 2013). Furthermore, not all studies corrected for multiple comparisons when using test batteries (Andrews & Westerman, 2012; Bunce et al., 2012; Park et al., 2011), which might overestimate the observed associations to a certain degree.

Furthermore, only limited evidence was available for evaluating the physiological brain dynamics related to driving performance in young and older populations. One of these studies did not evaluate brain activity while actually driving in a simulator (Eudave et al., 2018). Finally, the choice was made to only include studies that evaluated driving performance in a simulator. Even though the use of a driving simulator has several advantages, such as the possibility to evaluate driving ability in a standardized and safe environment and allow the assessment of a variety of driving related measures, it remains a question if simulator-based driving reflects actual real world on-road driving (Helland et al., 2016). Nevertheless, there is positive evidence available on the validity of a driver simulator assessment for evaluating older drivers' performance (Aksan et al., 2016; Lee et al., 2003).

5 Conclusions and future directions

This systematic review found evidence that several domains of cognitive functioning, irrespective of age, are associated with driving simulator performance. Especially the cognitive domains of executive function, complex attention, and therefore also dual tasking ability, are important for adequate driving performance in both younger and older adults. However, with increasing age, cognitive performance tends to deteriorate, which might explain poorer driving performance in older adults. The older persons drove less consistently than the younger adult drivers, as demonstrated by a larger variability in speed, headway, i.e. the distance or time from the lead car during car-following situations, and lane keeping performance. Evidence was also found that older drivers will compensate for age-related cognitive decline by driving slower, in order to cope with larger task demands during driving. Therefore, at risk older persons could benefit from strategies focusing on reducing task demands, such as training of dual tasking abilities in a driving context, or for instance recommending vehicles with automatic gear transmission.

At this moment, it is still unclear if older drivers with a similar cognitive performance as younger adult drivers also have a similar driving performance. There is an indication that this might be the case, with one EEG study finding differences in the neural correlates between high and low performing older adults, and the high performing older drivers having similar driving results as the younger persons. Still, more research should focus on understanding the inter-individual variability between older drivers in order to develop tailor-made intervention strategies.

Only a limited amount of studies evaluated the neural correlates of driving in an aging population. It is probable that the differences in the underlying brain dynamics between young and older drivers account for a deterioration in older driver performance, which is supported by the findings of the EEG studies that older drivers experience a higher cognitive load. Nevertheless, future research should try to implement neuroimaging techniques to further explore the neural correlates of driving performance. Furthermore, it might be useful to implement neuromodulation techniques to explore the causal association between neurophysiological processes and their association with driving. This could offer a unique perspective in the field of driving research, as portable neuromodulation systems could be used as a preventive measure for motor vehicle crashes. Finally, due to the complexity of driving performance and diversity in driving evaluation, future driving simulator research and clinical screening application could benefit from a general construct of outcome measures to objectify driving performance.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

SD: Conceptualization, Methodology, Writing - original draft, Visualization, **VR:** Supervision, Writing - Review & Editing, **SV:** Writing - Review & Editing, **KB:** Writing - Review & Editing, **TB:** Supervision, Writing - Review & Editing, **KvD:** Validation, Supervision, Writing – Review & Editing, **RM:** Supervision, Writing - Review & Editing

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