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Take-over Performance of Older Drivers in Automated Driving: a Review

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Abstract

Introduction: The introduction of automated vehicles to the road environment brings new challenges for older drivers. Level 3 of conditional automation requires drivers to take over control of their vehicle whenever the automated system reaches its limits. Even though autonomous vehicles may be of great benefit to older drivers in terms of safely maintaining their mobility, a better understanding of their take-over performance remains crucial. The objective of this review of the literature is to shed more light on the effects that aging has on take-over performance during automated driving.

Methods: Three database searches were conducted: PsychINFO, Web Of Sciences, and TRID. Studies from the last decade which included groups of older drivers were reviewed.

Results: After checking through abstracts and texts of articles, 9 articles, 4 proceedings papers, and 1 technical report were included in this review. All studies included a driving simulator that refers to level 3 of automation (which requires supervision by the driver). Five out of fourteen studies showed that older adults had poorer take-over performances (in terms of take-over time and take-over quality) than younger adults. However, several factors, such as the type of non-driving related task (NDRT), were seen to influence take-over performance in older adults. Speed, type and duration of notification interval, distribution and duration of driving modes, and number of take-overs were all also factors of influence.

Conclusion: Findings from the studies selected yield divergent results, probably due to differences in their methodology or in the demographic characteristics of participants. This literature review highlights the need to develop new research on the impact of aging on take-over performance.

Highlights

- Level 3 of automated vehicles brings new challenges for older drivers
- This article reviews take-over performance in older adults during automated driving
- Results from the 14 driving simulator studies reviewed yielded no general consensus
- Five studies showed impaired take-over performances in older adults
- Recommendations for designing automated vehicles for older adults are proposed

Keywords

Older drivers – Automated driving – Take-over – Cognitive function– Simulator

1. Introduction

As life expectancy increases, the number of older adults is expected to rise in the future. In France, according to the National Institute of Statistics and Economic Studies, the proportion of people aged 65 or more will increase steadily until 2040, and will represent one in four inhabitants (<https://www.ined.fr/>). The aging of the population therefore poses new challenges in terms of health and mobility. Recent advances in vehicle automation will change the way transportation and mobility function. Autonomous vehicles could benefit older adults by prolonging or even improving their mobility, security, autonomy and quality of life. However, the introduction of automated vehicles may pose specific challenges for older drivers in terms of road safety.

The International Society of Automotive Engineers (SAE International) has classified and defined six levels of driving automation. These levels range from a manually operated car (no automation) to full automation (SAE, J3016). The present review focuses on level 3, in which the system performs all aspects of driving, such as car-following and maintenance of lane position. However, the driver must be ready to take back control when the automated system issues a request, for example when a critical situation occurs, or on a section of road that the system cannot handle (SAE, J3016). As some studies have shown, take-over maneuvers can sometimes be more challenging for older adults due to age-related decline in physical, sensory and cognitive abilities (Molnar et al., 2017; Körber et al., 2016).

The effects of age-related decline on global driving skills have been widely demonstrated (Renge et al., 2020). Changes in visual-perceptual abilities and executive functions may modify driving performance, especially in challenging traffic situations such as dense traffic, complex junctions or in situations involving high temporal constraints (Fausto et al., 2021). Reduction of the visual field leads to a decreased ability to register relevant information while driving, and results in an increased risk of accident (Ball & Owsley, 1991). A meta-analysis showed that

slower processing speed in visual attention tasks (measured by the Useful Field of View Test) is associated with a higher risk of accident, as well as poorer performance on the road and in the driving simulator (Clay et al., 2005). Older drivers with cognitive deficits display a significant deterioration in driving behavior (Brouwer et al., 2002). Their ability to concentrate, to make quick decisions and avoid other vehicles or pedestrians is more impaired than in younger drivers (Fausto et al., 2021). The link between age-related executive deficits, assessed by neuropsychological tests (e.g. the MMSE or Trail Making Test B), and crash risk (Daigneault et al., 2002) and driving safety has been shown in different studies. MMSE scores can predict some aspects of poor driving performance in older drivers (Renge et al., 2020). Poorer performance in the Trail Making Test B can also predict failure in on-road driving tests (Classen et al., 2013 ; Lafont et al., 2010; Ranchet et al., 2013).

Over the last few years, 129 studies have investigated the determinants of take-over performance for level 3 conditionally automated vehicles (for a meta-analysis, see Zhang et al., 2019). Few studies have, however, focused specifically on older adults, and little is known about the effects of age-related cognitive decline on take-over. During a take-over maneuver, several successive and complex actions, involving many perceptual and cognitive skills must be performed within a constrained timeframe. First of all, drivers need to perceive the take-over request in order to perform the maneuver at the right time. The take-over request can be made in the auditory modality (a sound) and/or in the visual modality. This requires rapid processing and a good understanding of the auditory alert or visual information. Drivers then need to disengage their attention from the non-driving related task (NDRT) to redirect it towards the take-over request. This cognitive process requires the involvement of a flexibility mechanism, which is essential when attention has to be shifted from one object or level of focus, to another. Two complementary abilities, selective attention and inhibition, are also involved. Selective attention allows attentional resources to be focused on information which seems relevant during

performance of the task. The inhibition mechanism intervenes to block any irrelevant information which could distract the driver. These abilities allow drivers to focus their attention on carrying out the take-over, and to block out all other information unrelated to the driving task. Finally, the take-over maneuver requires good psychomotor skills and motor coordination so that driving can be taken over quickly and effectively. The literature suggests that executive function, complex attention and dual tasking all affect take-over performance in older adults (Depestele et al., 2020). Although some previous empirical studies have examined the effects of age on take-over performance, no literature review has, as yet, summarized all the results and factors which influence takeover performance in older adults. The present literature review provides an overview of studies which have investigated take-over performance in older adults. Its objectives are 1) to synthesize the results of studies dealing with the take-over issue in older drivers, 2) to discuss the various factors that can affect take-over performance, particularly in older adults, and 3) to suggest a number of directions future research on the impact of aging on automated driving might take.

2. Methods

2.1. Data sources and searches

The authors developed the search strategies with the assistance of an academic librarian (N.B.). The search of the literature was made using a combination of keywords including a) older adults; b) takeover or take-over c) driving automation. In order to identify the relevant studies, the first concept was combined with concept c), and then with concept b). The research strategy was conducted on 3 databases: Web of Sciences, Scopus and Transport Research International Documentation (TRID). The request was (((elder* OR senior* OR old* AND adult* OR aged OR ageing OR aging OR geriatric OR age OR older AND driv* OR age AND difference OR human AND factors)) AND (auto* OR self-driving OR highly AND

auto* AND driving OR auto* AND driving OR human-auto*-interaction OR conditional AND auto* OR highly AND auto* AND vehicle OR self-driving AND vehicles)) AND (take-over AND request OR takeover AND request OR take-over AND quality OR takeover AND quality OR take-over AND performance OR takeover AND performance OR control AND transition OR driv*take-over OR driv* AND takeover OR take-over AND performance OR takeover OR transfer AND of AND control. Only articles and proceedings papers written in English and published in the last ten years up to January, 20 2022 which examined conditional automation (level 3 of SAE) were included. All searches resulted in a total of 418 articles, including duplicates. A manual search of articles for additional studies was also performed.

2.2. Study selection

For the purpose of this review, all prospective or retrospective case series, comparative, case-control and cohort studies, and randomized controlled trials were selected on a number of eligibility criteria: (i) studies which included at least one group of older adults, (ii) studies published in English, in a scientific review or as conference proceedings, (iii) studies published between 2011 and 2022. No criteria on the average age of older participants were specified. Case reports ($n < 10$), editorials, guidelines, letters, and reviews were excluded.

2.3. Study and data extraction

Titles and abstracts were scanned for relevance by two independent reviewers (M.R and L.P.F) ($n = 91$). After screening, the full texts of articles were appraised independently by the two reviewers to confirm their eligibility ($n = 15$). When the reviewers disagreed, a discussion took place between the two authors to reach the final decision on eligibility. In the end, 14 articles were included in this review of the literature. Cohen's kappa = 0.75, reflected agreement

between the two authors, and indicated strong agreement regarding full text screening. The flow chart (Figure 1) describes the systematic review process.

Extracted data included firstly the author’s name and year of publication, information about participants (number of adults, age), type of NDRT, speed, type and interval of notification, duration of manual and automated zones, number of take-overs, main outcomes (driving measures, NDRT scores, questionnaires) and key findings.

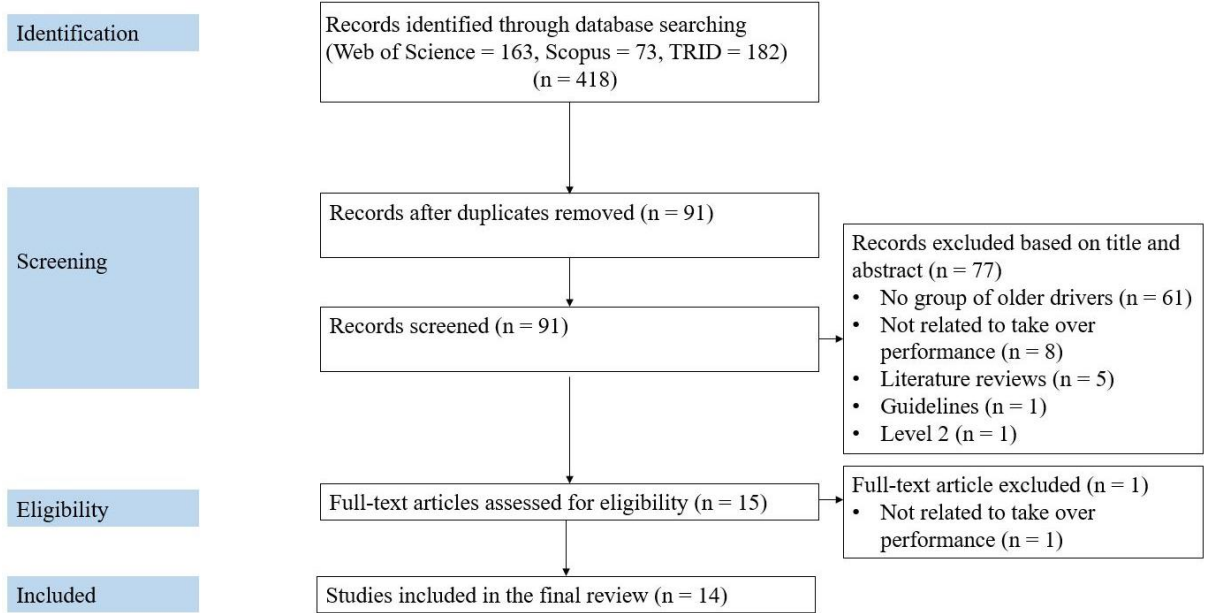


Fig. 1. Flow chart of the literature review

3. Results

Table 1 presents all 14 articles reviewed in this study. The main purpose of each study was to examine take-over performance in older drivers in comparison to that of younger drivers. Take-over performance is usually assessed using a driving simulator. Two aspects of take-over performance can be studied: take-over time and quality of take-over. Take-over time corresponds to the time between the take-over request (TOR) and the moment the driver takes back control of the vehicle (Li et al., 2018). A rapid take-over constitutes a good performance.

Take-over quality is usually assessed by: maintenance of direction (steering wheel angle), lane position (staying in lane), speed adaptation (speed variability), avoidance of collision (time to collision), number of collisions, critical event encounters, and lane deviation which corresponds to the maximum lane offset after the TOR (Favarò et al., 2019). In table 1, studies appear in alphabetical order (based on the main author's name) and by date of publication (column 1). The table includes information on the number of participants, the mean age of each group (column 2), the type of NDRT performed during automated driving before the take-over (column 3), the speed of the automated system when take-over was requested (columns 4), the type of notification (auditory or visual), and the interval of notification (column 5). The table also includes information, when available, about the duration or the distance of each phase (manual, automated, and take-over) and the distribution of each driving mode, i.e. whether they appeared randomly or not (column 6), the number of take-overs (column 7). The dependent variables, such as the driving measures used to assess take-over performance, NDRT scores and the type of questionnaire administered are specified (column 8). Finally, for each dependent variable, results from older adults are compared to those of younger adults (column 9). Findings comparing different driving conditions (e.g., with or without an NDRT; with or without HMI) for each age group are reported in the last column (column 9).

This section firstly presents the key findings on take-over performance in older adults compared to that of younger adults. The results are then commented column by column to determine the extent to which the different factors contribute to take-over performance in older adults.

Table 1. Findings from reviewed studies on older drivers and take-over performance.

Author (year)	Participants	Types of NDRT	Speed	Type of notification (notification interval)	Manual zone / automated zone / take-over zone	Number of take-overs	Main outcomes	Comparison results of between-group and within-group differences
Clark & Feng, (2016)	17 YD (18 to 35, M= 19.9 years) 18 OD (62 to 81, M= 70.4 years)	Voluntary NDRT	72 KM/H	Auditory notification: two beeps, first 350 Hz and then 400 Hz. (4.5s or 7s)	Unchanged / randomly selected between 1.5 and 2 min / 0.12 km	12	SD of steering wheel angle	OD = YD
							Speed	OD < YD
							SD of lane position	OD < YD
							Brake input pressure	OD > YD
							Throttle input pressure	OD > YD
Notification response time	OD = YD For OD: longer notification interval < shorter notification interval For YD: longer notification interval = shorter notification interval							
							Total duration of each NDRT	OD < YD
Clark et al. (2017)	17 YD (M = 19.9 years) 17 OD (M= 70.2 years)	Voluntary NDRT	72 KM/H	Auditory notification: two beeps, first 350 Hz and then 400 Hz. (4.5s or 7s)	Unchanged / randomly selected between 1.5 and 2 min / 0.12 km	12	Average speed during take-over	OD: age is negatively correlated with speed YD: age is positively correlated with speed
							Take-over response time to a take-over notification	YD responded to the take-over faster when they had a higher number of activity engagements
Favarò et al. (2019)	12 YD 18-35 (M = 25)	∅	55 MPH (88.5 km/h) or 65 MPH (104.6 km/h)	Oral warning “Danger! Take back control”	NS / NS / NS	1	Lane Drift	OD = AD = YD
	12 AD between 35 and 55 (M = 46)			Warning displayed on central console display, and featured an exclamation mark inside a chartreuse yellow triangle along with a symbol of hands on a steering wheel.			Speed	OD < YD
	12 OD older than 55 (M = 60)							
Körber et al. (2016)	36 YD (19 to 28, M= 23.3 years, SD= 2.60) 36 OD (60 to 79, M= 66.7 years, SD= 4.56)	20 Questions Task	120 KM/H	Auditory double beep 2800 Hz 74 dB (7s)	NS / NS / NS	9	Take-over time	OD = YD
							Maximum lateral acceleration	OD = YD
							Minimum TTC Number of collisions	OD > YD OD < YD

							Braking pressure when the traffic density was zero or medium	OD > YD
Li et al. (2018)	37 YD (20 to 35, M= 26.05, SD= 4.47 years) 39 OD (60 to 81, M= 71.18, SD= 6.06 years)	Read aloud the material displayed on an iPad for one minute	0 to 30mph (48km/h) on city road 60mph (96 km/h) on motorway	Visual: prominent red message on the screen reading "Please take-over" and auditory: female voice saying "Attention! Please take-over vehicle control" (20 s)	20 s / 1 min / 20 s	8	Reaction time Indicator time Take-over time TTC Resulting acceleration Steering wheel angle Total number of Collisions and critical encounters	OD > YD OD > YD OD > YD OD < YD OD > YD OD > YD OD > YD
Li and al. (2019a)	37 YD (20 to 35, M=26.05, SD=4.47 years) 39 OD (60 to 81, M=71.18, SD=6.06 years)	Two driving Disengagement Levels (DDL): Disengagement from driving: read aloud the material displayed on an iPad for one minute Monitoring driving	0 to 30mph (48km/h) on city road 60mph (96 km/h) on motorway	Visual: prominent red message on the screen reading "Please take-over" and auditory: female voice saying "Attention! Please take-over vehicle control" (20 s)	20 s / 1 min / 20 s	NS	Reaction time Take-over time Indicator time TTC Resulting acceleration Steering wheel angle	OD > YD With age: Disengagement from driving > Monitoring driving OD > YD With age Disengagement from driving > Monitoring driving OD > YD With age: Disengagement from driving > Monitoring driving OD = YD With age: Disengagement from driving < Monitoring driving OD > YD OD > YD
Li et al. (2019b)	37 YD (20 to 35, M= 26.05, SD= 4.47 years) 39 OD (60 to 81, M= 71.18, SD= 6.06 years)	∅	0 to 30mph (48km/h) on city road 60mph (96 km/h) on motorway	Baseline HMI voice "attention please take-over control of the vehicle" Reasons for take-over (R): "attention please take-over control of the vehicle and respond to the parked car ahead" Vehicle status (V) "attention please take-over control of the vehicle" + before TOR voice	20 s / 1 min / 20 s	4	Reaction time Indicator time Take-over time TTC Resulting acceleration Steering wheel angle Reaction time and take-over time NASA-RTLX workload score	OD > YD OD > YD OD = YD OD > YD OD > YD OD: Baseline HMI > R HMI > V HMI and the R + V HMI YD: baseline HMI < R HMI OD > YD

				said “the vehicle is in highly automated driving mode at 30/60 mph” R + V HMI (20s)				OD’s workload: Baseline HMI > R HMI > V HMI and the R + V HMI YD’s workload: Baseline HMI < R HMI R HMI > V HMI V HMI > R + V HMI
Li and al. (2021)	15 YOD (60 to 69, M=64.97, SD=3.46 years) 24 OOD (70 to 81, M=75.13, SD=3.35 years)	Read aloud the material displayed on an iPad for one minute	0 to 30mph (48km/h) on city road 60mph (96 km/h) on motorway	Visual: prominent red message on the screen reading “Please take-over” and auditory: female voice saying “Attention! Please take-over vehicle control” (20 s)	20 s / 1 min / 20 s	NS	Reaction time Indicator time Take-over time TTC Resulting acceleration Steering wheel angle Total number of Collisions and critical encounters Positive attitude toward the automated vehicle	OOD > YOD OOD = YOD OOD > YOD OOD < YOD OOD > YOD OOD > YOD OOD > YOD OOD > YOD
Miller et al. (2016)	12 YD (15 to 18, M= 16.8, SD= 0.92 years) 12 MAD (17 to 69, M= 28.4, SD= 13.21 years) 12 OD (70 to 81, M= 73.3, SD= 5.17 years)	Reading a selection from a book or watching a selection from a movie or supervising the ADAS	NS	Voice command and visual indication on the instrument panel (5s)	30 s / 8 min 30 / 5 s	3	Speed Speed after transition from automated driving Collision Avoidance Strategies to avoid a critical event (car-cut off or pedestrian incursion) Self-reported driving style: Anxiety dimension Risky driving Patience	OD < MAD and YD OD and MAD < YD OD = MAD = YD OD used combination of braking and steering strategies YD and MAD used primarily braking strategies OD and YD < MAD OD and MAD < YD OD > MAD and YD
Mok et al. (2016)	20 YD (15 to 19, M=17, SD= 0.94 years) 40 AD (18 to 66, M= 26.2, SD= 12.1 years) 20 OD (60 to 77, M= 67.5, SD= 6.13 years)	∅	35 and 70 mph	Audio alert (NS)	2 min / 12 min / NS	1 for the group “takeover” As many times as the participant wants for the group “takeover + influence”	Number of participants who intervened to take-over in imperfect driving Self-Reported Attitudinal Data	OD < AD YD = AD Seniors rated their driving performance as significantly worse than the automated driving system
Molnar et al. (2017)	24 YD (16 to 19 years)	∅	NS	Verbal: “handing-back control”, visual: a change in the background of	Drivers drove manually until they were comfortable giving control back	7	Take-over reaction time Proportion of manual disengagement	OD and MAD > YD OD and MAD < YD

	24 MAD (25 to 45 years)			the instrument cluster from green (automated mode) to yellow (handover mode), and haptic: a buzzing of the seat with the haptic actuators (vibrating seat) (5s)	to the automation / NS / 5 s		Disengagement time	OD and MAD > YD
	24 OD (65 to 75 years)						Gaze dispersal during automated mode	OD and MAD < YD
							Percentage of time eyes off road	OD and MAD < YD
							Proportion of disengagement type	OD and MAD < YD
							NASA-TLX Mental Demand sub-scale	OD > MAD and YD
Peng & Iwaki, (2020)	27 YD (M= 28.1, S = 4.7 years)	n-back task (1-back task)	90 km/h	Auditory (100 meters or 4 s time to collision)	NS / NS / NS		Collision rate	OD > YD
	27 OD (M= 73.0, SD= 3.63 years)						Standard deviation of steering wheel	OD > YD
							Number of Fixation Transition Between AoIs	OD < YD
							- with NDRT	OD < YD
							- with high traffic density	OD < YD
							Fixation duration on mirrors	OD < YD
							- with NDRT	OD < YD
							- in high density traffic	OD < YD
Wu et al. (2019)	115 participants with 5 age groups: 20 or younger, 30, 40, 50, and 60 and older	∅	60 KM/H	Auditory + visual (20 s)	Three experimental conditions: Auto-3: NS/ 3 min / NS Auto-31: NS/ 31 min / NS A-M-A: 10 min/ twice 10 min separated by 10 min of manual driving / NS	1 per condition	TOR performance: Reaction time for effective steering	With age: A-M-A > Auto-31
	84 participants performed the Auto-31 test; 28 remaining participants performed the A-M-A test						Reaction time for the braking operation	With age: A-M-A > Auto-31
							Reaction for taking over control	With age: A-M-A > Auto-31
							SD of the steering wheel	Effect of age ^a
							TTC	With age: A-M-A < Auto-31
							Drowsiness measures: Karolinska Sleepiness Scale	Effect of age ^a

						Eyeblink duration	Effect of age†	
Wu et al. (2020)	12 YD (19–32, M= 24.6 SD= 4.9 years)	No NDRT engagement (Non-NDRT)	60 km/h	Auditory: verbal message to take-over control and visual alert :(a changed symbol on the vehicle instrument panel) (NS)	60 s / 30 min / 6 s	3	TOR performance: - Reaction time: Time lapse after TOR until the steering wheel was turned right by 2 degrees	YD: Non-NDRT > Video-30 and V-G-V (trend) MAD: Non-NDRT < Video-30 and V-G-V OD: Non-NDRT < V-G-V
	12 MAD (37–50, M= 43.9, SD= 4.5 years)	With NDRTs: Single task: watching a video clip for 30 min (V) (Video-30)					-Standard deviation of the steering wheel	OD : Non – NDRT < V-G-V condition
	12 OD (56–74, M= 64.3, SD= 5.6 years)	Multiple tasks: V, playing a game, V (V-G-V)					Drowsiness measures: -Karolinska Sleepiness Scale. Score difference	YD: Non-NDRT > Video-30 and V-G-V MAD: Non-NDRT and Video-30 > V-G-V OD: non NDRT = Vdeo-30 = V-G-V
							- Eyeblink duration (Average eyblink duration of the final 2-minute epoch before TOR)	YD: Non-NDRT > Video-30 and V-G-V MAD: Video-30 > V-G-V OD: non NDRT = Video-30 = V-G-V

Abbreviations. AD=adult drivers, M=mean age, MAD=middle aged driver, Min=minutes, NS=not specified, NDRT=non-driving related task, OD=older driver, OOD=older old driver, S=second, SD=standard deviation, TOR=take-over request, TTC=time to collision, YD=young driver, YOD=younger older driver, =: equal, ≠: different, ∅ =absence, † means that poorer performance was found with advancing age.

OD > YD means that younger drivers had lower scores and shorter RT than OD

OD < YD means that younger drivers had higher scores and shorter RT than OD

YD = OD indicates no significant difference between groups

Take-over performance

Globally, all studies except one, (Mok et al., 2016), investigated take-over performance when this was imposed by the system (for instance, when an unexpected event occurred on the road) and was not chosen by the driver. Overall, most studies showed impaired take-over performance in terms of time and quality of take-over. However, three studies showed no pronounced differences in the take-over performances of older adults and younger adults (Favarò et al., 2019; Körber et al., 2016; Miller et al., 2016). Most studies that have investigated the time aspects of take-over have reported that take-over performance is poorer in older drivers than in younger adults. Take-over times, and the time taken to react to a take-over notification are both longer in older adults than in younger adults (Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Molnar et al., 2017; Wu et al., 2019). This take-over time is even longer in older drivers of a more advanced age (mean age: 75 years-old) (Li et al., 2021). However, two studies found no differences in time to take-over between older and younger drivers (Clark & Feng al, 2016; Körber et al., 2016). Most studies that examined take-over quality found that take-overs by older drivers were less effective than in younger drivers. In most studies, driving speeds during take-over or after transition from automated driving were slower in older drivers than in younger drivers (Clark & Feng, 2016; Clark et al., 2017; Favarò et al., 2019; Miller et al., 2016). In terms of steering wheel control during a take-over, most studies showed that older drivers' performances were worse than those of younger drivers. Steering wheel variation appeared to be greater in older drivers, and this could be seen in the difficulty they experienced when trying to keep to the car in lane (Li et al., 2018; Li et al., 2019a; Li et al., 2021; Peng & Iwaki, 2020; Wu et al., 2019). However other studies showed that neither lane deviation performance nor steering wheel angle seemed to be affected in older drivers (Clark & Feng, 2016; Favorò et al., 2019).

The actions of older drivers appeared to be more ‘brutal’ than those of younger drivers. Older drivers applied more pressure to the brake and throttle during takeover (Clark & Feng, 2016; Körber et al., 2016) and had greater resulting acceleration (Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021).

The number of collisions and the number of critical encounters during take-over are higher in older drivers than in younger drivers (Peng & Iwaki, 2020; Li et al., 2018. Li et al., 2021). Similarly, the TTC is shorter in older drivers than in younger drivers in some studies (Li et al., 2018; Wu et al., 2019). Furthermore, the TTC is even shorter in older-old adults than in younger-old adults (Li et al., 2021). Other studies showed that the TTC did not differ between the two groups (Li et al., 2019a; Li et al., 2019b). One other study showed a contrary result, with longer TTCs in older drivers than in younger drivers (Körber et al., 2016).

In self-reported assessments, older drivers report being less successful at performing takeovers than younger drivers (Mok et al., 2016).

In older drivers, the scope of visual exploration during take-over was reduced compared to that of younger drivers (Peng & Iwaki, 2020; Molnar et al., 2017). Older drivers made fewer transitions between different areas of interest (rearview/left/right mirror, front road, driver HMI), and the duration of their fixations on mirrors was also shorter than for younger drivers (Peng & Iwaki, 2020). Moreover, the width of descending vertical visual scan was diminished in older drivers compared to younger drivers (Molnar et al., 2017)). Furthermore, the percentage of times the eyes of older adults were not directed at the road was lower during automated driving than during manual driving (Molnar et al., 2017).

It was also observed that neither single nor multiple engagements in NDRTs prevented the emergence of drowsiness in older drivers (Wu et al., 2020).

Factors that influence take-over performance

Non-driving-related tasks

Nine out of 14 studies investigated the impact of NDRTs on take-over performance in older drivers. NDRTs vary considerably from one study to another. In some studies, NDRTs are voluntary tasks where participants choose their activity (Clark & Feng 2016; Clark et al., 2017). In others, participants are required to respond to a series of questions during the take-over (Körber et al., 2016), to read aloud (Li et al., 2018; Li et al., 2019a; Li et al., 2021) to read an extract from a book (Miller et al., 2016) or watch a video (Miller et al., 2016; Wu et al., 2020), to play a game (Wu et al., 2020), or to complete an n-back task (Peng & Iwaki, 2020). Participants could be asked to engage in a single NRDT, such as watching a video-clip, or in multiple NRDTs, such as watching a video clip, playing a game, and then watching a video clip again (Wu et al., 2020).

Clark & Feng. (2016) showed that voluntary engagement in an NDRT did not impair take-over performance in general. However, the behavior of older drivers before, during, and after the take-over differed from that of younger drivers. Both groups engaged in various NDRTs during the automated driving phase, with distinct preferences for the type of activity in each age group: older drivers tended to converse, whereas younger drivers mostly used an electronic device. Contrary to young drivers, older drivers responded quickly to TOR when the notification interval was long, suggesting that older drivers benefited more than younger drivers from the longer notification interval. When the notification interval was short (4.5s), older drivers who were more engaged in an NDRT (high activity group) tended to brake harder than those with low activity-engagement during the take-over. According to the authors, it is possible that braking harder is related to some degree of impairment in take-over performance. After a take-over, older drivers generally drove more slowly and deviated less from the centerline of the road.

Clark et al. (2016) classified voluntary NDRTs into three cognitive dimensions: visual-manual; auditory-manual; and auditory-vocal. The authors showed that in younger drivers, when the number of activities during automated driving was higher, response times to a take-over notification decreased. However, this was not the case for older drivers. Younger drivers' response times to a take-over notification were faster when they were engaged in a greater number of activities during automated driving. In contrast, when the number of activities increased, older drivers' response times to a take-over notification were not faster. Miller et al. (2016) did not find any significant differences of the effect of NDRTs on driving performance between older and younger groups. The effect of NDRTs on drowsiness differed depending on the age of the driver. Engagement in multiple NDRTs helped to prevent drowsiness during automated driving in younger drivers and in middle-aged drivers. However, neither single nor multiple engagements in NDRTs prevented the emergence of drowsiness in older drivers. Moreover, take-over performance altered significantly in older drivers when they were engaged in multiple NDRTs. They reacted more slowly, and steering stability worsened. Another study showed that a long duration of engagement in NDRTs had a negative effect on lane offset (Favarò et al., 2019). When drivers were engaged in an NDRT, they made fewer transitions between areas of interest, and had shorter fixation durations on mirrors than in the absence of an NDRT (Peng & Iwaki, 2020). They had also longer reaction times, take-over times and indicator times (Li et al., 2019a). In addition, when older drivers were engaged in an NDRT, their TTC was shorter than that of younger drivers in the same condition (Li et al., 2019a).

Speed:

Twelve studies out of 14 specified the speed of the vehicle during the automated driving phase. 6 studies defined a fixed speed: 60 km/h (Wu et al., 2019; Wu et al., 2020), 72 km/h (Clark & Feng, 2016; Clark et al., 2017), 90 km/h (Peng & Iwaki, 2020), 120 km/h (Körber et al., 2016).

In the other 6 studies, the speed setting of the vehicle varied during the automated driving phase (Mok et al., 2016; Favarò et al., 2019; Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021). Some of the studies that compared the take-over performances of younger and older adults showed similar results, irrespective of vehicle speed (72 km/h, 120 km/h) in the automated phase (Clark & Feng, 2016; Körber et al., 2016): take-over time did not differ between age groups. Speed after the take-over was slower in older adults than in younger adults. However, four other studies using vehicle speeds of 48 km/h, 96 km/h, and 90km/h in the automated driving phase showed greater steering wheel variability and a higher number of collisions (Li et al., 2018; Li et al., 2019b; Li et al., 2021; Peng & Iwaki, 2020). Only one of the studies in which the speed setting varied showed an impact of the speed setting (88.5 km/h or 104.6 km/h) on maximum lateral offset after the TOR (Favarò et al., 2019). The increase in speed of the automated vehicle by 16 km/h (10 mph) more than doubled the average maximum offset. Furthermore, participants in the older group (55+) performed best at the low speed setting, and performed comparably to the other age groups at high speeds (Favarò et al., 2019). The other 4 studies did not specifically investigate the effects of speed setting on take-over performance in older adults (Li et al., 2018; Li et al., 2019b; Li et al., 2021; Mok et al., 2016).

Type and duration of notification:

The type of notification was either auditory (Clark & Feng, 2016; Clark et al., 2017; Körber et al., 2016, Mok et al., 2016; Peng & Iwaki, 2020), visual and oral (Favarò et al., 2019; Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021; Miller et al., 2016; Wu et al., 2019; Wu et al., 2020), or oral, visual and haptic (Molnar et al., 2017). These previous studies did not specifically investigate the effects of the type of notification on take-over performance in older adults.

Another study investigated the effects of different types of Human-machine interaction (HMI) on take-over performance in older adults (Li et al., 2019b). Four types of HMI, ranging from simple to complete, were defined. Before the take-over request, the HMI either delivered an oral message to take-over (baseline HMI), or indicated orally the speed of the automated drive and/or the reasons for the take-over. Older and younger drivers reacted more quickly to the TOR when the HMI indicated the vehicle's status and the reasons for the take-over orally, and when the HMI indicated only the vehicle status, than to the baseline HMI or the HMI indicating the reasons for the take-over. Interestingly, the HMI indicating the reasons for the take-over affected older and younger drivers in opposite ways. Compared to the Baseline HMI, the HMI indicating the reasons for the take-over reduced reaction times, takeover times and workload in older drivers, and increased these variables in young drivers. Finally, the authors concluded that the HMI indicating both the reasons for the take-over and the vehicle status was the most effective, since in both groups take-over performance was better, workload was lower and levels of positive attitude were higher.

The duration of notification could be 4s (Peng & Iwaki, 2020), 4,5s (Clark & Feng, 2016; Clark et al., 2017), 5 s (Miller et al., 2016; Molnar et al., 2017), 7 s (Clark & Feng, 2016; Clark et al., 2017; Körber et al., 2016), or 20 s (Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021; Wu et al., 2019). Only one study investigated the effects of the notification interval on takeover performance in older adults (Clark & Feng, 2016). Contrary to young drivers, older drivers responded quickly to a TOR when the notification interval was long, suggesting that older drivers benefit more than younger drivers from the longer notification interval. When the notification interval was short (4.5s), older drivers who were more engaged in an NDRT (high activity group) tended to brake harder than those with low activity-engagement during the take-over.

Distribution and duration of each driving mode (automated, manual, take-over)

The duration of the manual phase varied from 20 s to 10 minutes. The duration of the automated phase varied from 1 minute to 31 minutes. The take-over zone can be indicated in number of km (0.12 km for Clark & Feng, 2016, Clark et al., 2017) or in seconds (5s, Molnar et al., 2017; Miller et al., 2016, 6s, Wu et al., 2020, or 20s, Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021). One study compared the effects of different durations of scheduled manual driving on driver drowsiness, and on take-over request performance in older adults (Wu et al., 2019). In this study, scheduled manual driving was performed after three different durations of automated drive. The duration of the first automated drive was three minutes, the second one involved 30 minutes of automated driving, and the third condition was a scheduled manual drive during which participants were required to switch between automated and manual driving twice. Each driving phase lasted 10 minutes. This last condition was designed to maintain a higher arousal level. Participants were instructed to take-over the vehicle when a van stopped in front of the driver's vehicle. Main findings showed that the oldest drivers' reaction times to the take-over request were longer in the third condition (where participants were required to switch between automated and manual driving) than in the second condition (30 minutes of automated driving). The authors concluded that it would be better to avoid unnecessary task-switching between manual and automated driving for older drivers. In 3 of the studies reviewed, the duration of each driving mode was not defined (Favarò et al., 2019; Körber et al., 2019; Peng & Iwaki, 2020).

Number of take-overs

As displayed in Table 1, the number of take-overs differs considerably between studies: 1 (Favarò et al., 2019; Mok et al., 2016; Wu et al., 2019), 3 (Miller et al., 2016; Wu et al., 2020),

4 (Li et al., 2019b), 7 (Molnar et al., 2017), 8 (Li et al., 2018), 9 (Körber et al., 2016), or 12 (Clark & Feng, 2016; Clark et al., 2017). When the number of take-overs was high (> 7), half of the studies showed that older adults performed the take-over relatively well. Their take-over times were equivalent to those of young adults and TTC was longer (Körber et al., 2016). They adapted their driving behavior: they reduced speed after a TOR (Clark & Feng, 2016), and applied more pressure to the brake (Clark & Feng, 2016; Körber et al., 2016). Only one study examined the influence of different types of take-over on younger drivers, adult drivers and older drivers (Mok et al., 2016). They compared two types of take-over. "Takeover" drivers could take-over the vehicle by pressing a button on the steering wheel. "Takeover + influence" drivers could take-over the vehicle in the same way as the other group, or by just taking hold of the steering wheel. When they released the steering wheel, the vehicle returned to automated driving mode. The results showed that the number of take-overs in older drivers was lower than that of adult drivers.

4. Discussion

This review on the literature provides an overview of existing studies on the effects of ageing on take-over performance. The review included a total of 14 studies in which a driving simulator was used. In these studies, drivers were requested to take back control of the vehicle when the automated driving system reached its limits. In this section we firstly discuss the findings on take-over performance in relation to age-related cognitive, visual and motor deficits. We then interpret the results in relation to external factors that could impact take-over performance in older adults. And finally, research perspectives are addressed.

Ten out of fourteen studies investigated the temporal aspects of take-over (e.g. response time to notification) and take-over quality (Clark & Feng, 2016; Clark and al., 2017, Körber et

al., 2016; Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Li et al., 2021; Molnar et al., 2017; Wu et al., 2019; Wu et al., 2020). Four other studies investigated only take-over quality (Favarò et al., 2019; Miller et al., 2016; Mok et al., 2016; Peng & Iwaki, 2020).

4.1. Take-over performance in relation to age-related cognitive deficits in older drivers

To sum up, the majority of studies showed that older adults are globally slower at taking over a vehicle than younger adults (Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Molnar et al., 2017; Wu et al., 2019). As they age, older drivers become slower at taking over control (Li et al., 2021). This may be due to age-related cognitive changes: older drivers may take longer to select, understand and process information. Only two studies found no significant between-group differences in the time needed to take-over (Clark et al., 2017; Körber et al., 2016). According to the authors, the absence of between-group difference in their studies could be explained by the NDRT itself, which did not involve a very high level of engagement. Participants could easily disengage from the task, allowing them to have sufficient cognitive resources to take-over the vehicle correctly. The level of engagement in a task and the possibility of disengaging from it plays a major role in performance of a takeover.

Findings on take-over quality are divergent. Some studies showed older drivers to be less effective at taking over than younger drivers (Li et al., 2018; Li et al., 2019a; Li et al., 2019b; Peng & Iwaki, 2020). As expected, take-over by older drivers also became less effective as they aged further (Li et al., 2021). Visual exploration during take-over was reduced in older drivers, and the duration of their fixations on mirrors was shorter than in younger drivers (Peng & Iwaki, 2020). These findings are consistent with the idea that aging is accompanied by a reduction in visual field capacity (Huisinigh et al., 2015) and impaired attentional processes. On examination of visual patterns and take-over performances in older adults, the authors concluded that they

had relatively poorer driving performances during take-overs than younger drivers (Peng & Iwaki, 2020). In contrast, three other studies showed no decline in the quality of take-over in older adults, compared to younger adults (Favarò et al., 2019; Körber et al., 2016; Miller et al., 2016). One explanation could be that older adults compensate for their cognitive deficits by using coping strategies or by adapting their driving behavior. For instance, the time to collision may be longer in older adults (Körber et al., 2016). They generally drive more slowly after the transition from automated driving than younger drivers (Favarò et al., 2019, Miller et al., 2016, Clark & Feng, 2016; Clark et al., 2017). Driving more slowly could give older adults more time to react to an unexpected event on the road. This is consistent with previous literature on older adults and manual driving. Most older drivers reduced the distance they travel, and their driving frequency (Molnar et al., 2014). This suggests that older drivers are usually aware of their own difficulties, and as a result are more careful when taking over control of a vehicle.

In situations where older drivers have to choose one way of driving (autonomous or manual driving), they performed fewer take-overs than younger drivers (Mok et al., 2016), contrary to what authors expected. The authors proposed an explanation for this: older drivers reported that they preferred to place their trust in the vehicle and to refrain from intervening. In addition, older drivers declared that their driving performance was worse than that of the automated driving system. Older drivers' positive perception of the automated vehicle increased when they saw that the vehicle was reliable (Haghzare et al., 2021; Li et al., 2021). However, older drivers' ability to accept automated systems does not explain why their takeover performance is worse than that of younger drivers. There is no relationship between acceptability and performance.

4.2. External factors determining takeover performance in older adults

In addition to the more internal factors related to the cognitive changes which accompany aging, other external factors (NDRTs, distribution of individual driving modes) may influence takeover performance, particularly in older adults. Findings may also be discussed in the light of the methodology used in each study (notification interval, type of notification, automated driving speed). Almost half of the studies reviewed investigated the effects of NDRTs on takeover performance. The type of activity, the presence or absence of choice (voluntary activity versus imposed cognitive tasks), the number and difficulty of NDRTs, as well as the level of engagement (Clark et al., 2017; Wu et al., 2020) may all explain the divergent results on takeover performance in older adults. For example, older adults preferred to converse, whereas younger drivers mostly chose to use an electronic device. In the Miller et al. (2016) study, participants were asked to watch a movie or read an e-book on a tablet. In Wu et al. (2020) study, participants watched a video clip or played a game, whereas in other studies, participants could choose the type of NDRT (Clark & Feng, 2016). In the Körber et al. (2016) study, participants performed a 20 questions task, which was considered to be the equivalent of a hands-free phone conversation. When older drivers were engaged in multiple NDRTs, they reacted more slowly when they had to take over control, and their steering stability was worse than when they were not engaged in any NDRT (Wu et al., 2020). Single or multiple engagements in NDRTs do not prevent drowsiness in older drivers during automated driving. The authors also showed that an NDRT induces a greater mental workload in older adults. Some studies found that older adults differed in their *modus operandi* (Clark & Feng, 2016; Clark et al., 2017; Körber et al., 2016): they tended to brake harder when they were more engaged in an NDRT than drivers with a low level of engagement during the take-over (Clark & Feng, 2016). Slower speed was also associated with more advanced age (Clark et al., 2017). Similarly, in the Körber et al. (2016) study, older adults braked more often and harder, and maintained longer

times to collision. Older drivers had poorer take-over performances when they were disengaged from driving than when they were monitoring their driving (Li et al., 2019a). Overall, older drivers were more troubled by the presence of an NDRT. These difficulties are probably related to the cognitive deficits discussed above.

Although a number of factors have been used in the methodology, very few studies have demonstrated the impact of speed, type and duration of notification, or duration of the automated phase on take-over performance in older adults. One study showed that older adults performed best when the speed setting was low, and performed comparably to the other age groups at high speed. The study in question also demonstrated the negative impact of higher speed on lane deviation (which corresponds to the maximum lateral offset) (Favarò et al., 2019). The HMI indicating the reasons for a take-over improved take-over performance in older drivers and worsened take-over performance in young drivers, compared to their respective baseline HMI measurements (Li et al., 2019). The authors of the study also highlight the fact that the HMI indicating both the reasons for a take-over and vehicle status was the most effective for both younger and older adults. Only one study chose to vary the duration of notification: 4 s or 7 s. It showed that older drivers responded quickly to the TOR when the notification interval was long, unlike younger drivers (Clark et al., 2017). Interestingly, the distribution of the automated/manual phases seems to have an impact on takeover performance in older adults (Wu et al., 2019). However, only one study compared the different types of distribution of the manual/ automated phases. Findings showed that older drivers had poorer take-over performances when they were required to switch between automated and manual driving than in situations involving 30 minutes of automated driving. Other external factors such as traffic conditions, the weather and the type of road may also affect take-over performance in older adults. Older drivers had more collisions and critical encounters (defined as any take-over behavior with a threshold value of a minimum TTC of less than 1.5s) in foggy

and snowy conditions than younger drivers (Li et al., 2018). Take-over time was better on city roads than on motorways in both younger and older groups (Li et al., 2018).

The number of participants and the number of take-overs requested may also explain divergencies between findings. For example, all articles which found differences in take-over quality had at least 17 participants per group, whereas Miller et al. (2016) and Favarò et al. (2019) had only 12 participants per group. It can also be assumed that a high number of take-overs requested by the system provides more accurate results on the time and quality of the take-over.

To sum up, the number of variables used to study take-over performance in older drivers is relatively large and the results are quite divergent, showing more degraded performance in older participants. As stated previously, these poorer results are probably related to the slight deficits that are known in this population.

4.3. Contributions of these studies

This review of the literature may provide new and greater insight into the design of highly automated vehicles which are adapted to the needs of older drivers.

In order to compensate for the slight age-related slowing down, it appears that the notification interval between the take-over request and the take-over must be of sufficient length to allow older drivers to perform the take-over correctly (Clark & Feng, 2016). Time and quality of take-over are faster and more successful with an interval of 7.5 seconds in older drivers than with a shorter notification interval (4.5 s.) (Clark & Feng, 2016).

The speed setting is an important parameter to consider during take-over performance. A lower speed of 88.5 km/h results in smaller lane offset than the higher speed of 104.6 km/h. Slower speed led to better vehicle control in drivers of all age groups (Favarò et al., 2019).

Adjustments to the equipment on autonomous vehicles could compensate for the difficulties experienced by older drivers in adverse weather conditions. For instance, Li et al. (2018) suggested projecting the driving environment onto the head-up display during take-over to give drivers better visibility. They also proposed a steering wheel stabilization system to compensate for the difficulty of take-overs in adverse weather conditions.

4.4. Directions for Future research

Very few of the studies reviewed investigated the effects of speed, type and duration of notification, or duration of the automated phase on take-over performance in older adults. The impact of each of these factors on take-over performance in older adults should be considered in future research.

Only one of the fourteen studies reviewed examined the number of participants who intervened to take-over (Mok et al, 2016). In the others, the number of take-overs was considered to be an indicator of acceptance (Molnar, 2018). Participants who took over often were considered to have less confidence in the automated system; their level of acceptance was lower. Results showed that younger drivers were more likely to take-over control from the automated system than older drivers. Trust in automated driving, reported after a simulated experience using the technology, has been shown to be an important component of acceptance of the technology (Molnar et al., 2018). Future studies should explore the impact of acceptance, experience, and trust in new technology on the number of take-overs and on take-over performance, particularly in older drivers.

It could be assumed that in the future, fitness-to-drive assessments in different countries will change with the introduction of automated vehicles onto the road. None of the fourteen studies reviewed investigated the visual, cognitive, and motor abilities which are required to take-over control of a vehicle safely. Future studies should also determine which neuropsychological tests best predict take-over performance in older adults. Based on the literature on older drivers and manual driving, and the cognitive mechanisms involved in take-overs, tests assessing flexibility (the Trail Making Test), information processing speed (the Symbol Digit Modalities Test) and inhibition (Stroop test) should be good predictors of take-over performance in older adults. Although neuropsychological tests should not be used on their own, they would provide more insight into cognitive deficits in older drivers that may contribute to impaired take-over performance. This could help in the development of new fitness-to-drive assessment methods and allow better assessment of take-over performance in older adults.

To our knowledge, no studies have included individuals with medical conditions, such as neurodegenerative diseases. Future studies should also determine the extent to which driving automation can help individuals with medical conditions to maintain their mobility, especially those who have cognitive, physical and/or sensorial deficits known to impair driving ability.

This review included only two studies using eye-tracking to assess visual exploration in older drivers during take-over (Molnar et al., 2017; Peng & Iwaki, 2020). Physiological measures such as eye-tracking may help to better understand visual exploration and consequently, take-over performance.

All studies included in this review were performed on a driving simulator. Although the simulator allows drivers to be in a reproducible and controlled environment, it does not reflect real-life driving. It is also possible that older adults had poorer take-over performances during simulated driving than during real driving, particularly if they were not sufficiently familiar with the driving simulator and if they had to perform unfamiliar NDRTs during automated

driving. Future research should also investigate age-related differences in take-over performance on real roads. Based on findings from simulator studies, we expect that, on real roads, most older drivers will be able to safely take-over control of a vehicle and adapt their driving behavior after the take-over by, for instance, reducing their driving speed. A safe way to assess take-over performance in older adults would be to ask them to drive on a closed road. Future research investigating take-over performance in older adults on specific closed roads (e.g Transpolis site in France) should be carried out.

5. Conclusion

This review synthesizes the results of 14 studies of takeover performance in older drivers. Its contribution lies in the fact that it sought to show the links between poorer take-over performance and age-related changes. This review of the literature highlights the need to develop new research on the impact of aging on take-over performance.

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