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The Effect of Age on Gaze Behavior in Older Drivers and Pedestrians – A Review

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Gaze behavior can play an important role in the safety of both older drivers and older pedestrians, and therefore evidence-based knowledge related to gaze behavior in the older population should be communicated to those professionals who regularly work with this group. A review of 25 studies examining the effect of age on gaze behavior in drivers and pedestrians was conducted. A number of differences in gaze behavior in older and younger drivers and pedestrians are observed, among them (a) when changing lanes, older drivers do not glance as frequently as younger drivers at three important areas – the rear view mirror, the left side mirror, and the left blind spot, and (b) older drivers have a smaller horizontal gaze amplitude compared to younger drivers. Several methodological concerns were observed, among them: a scarcity of data on gaze behavior and elderly pedestrians and a lack of intervention studies. Additional studies should examine the use of a vision-in-action paradigm and designated gaze-training interventions in both the elderly driver and elderly pedestrian populations, in order to reduce the number of motor vehicle accidents and pedestrian injuries among the older population.

Keywords: eye movement, eye tracking, attention, region of interest, transportation, older drivers, pedestrians

Introduction

In 2010, an estimated 524 million people were aged 65 or older – eight percent of the world's population at large (National Institute on Aging, 2015). By 2050, this number is expected to nearly triple to about 1.5 billion, representing 16 percent of the world's estimated population at large. In 2012, among those aged 65 and over, there were almost 36 million licensed drivers in the USA (Center for Disease Control and Prevention, 2015). This number of older drivers is a 34 percent increase from 1999.

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Driving helps older adults maintain their mobility and independence. However, human aging has been found to influence the risk of being injured or killed in a motor vehicle accident (Center for Disease Control and Prevention, 2015). For example, according to the National Highway Traffic Safety Administration (NHTSA; 2015), in 2012 more than 5,560 older adults were killed and more than 214,000 injured in motor vehicle accidents in the USA. This amounts to 15 older adults killed and 586 injured in motor vehicle accidents on average every day. In addition, per miles traveled, fatal motor vehicle accident rates increase noticeably starting at ages 70-74, and are highest among drivers age 85 and older.

Human aging is associated with a decline in a number of cognitive abilities, among them executive functions, episodic memory, and perceptual speed (Bäckman, Lindenberger, Li, & Nyberg, 2010; West, 1996). The concept of executive functioning has been extensively studied during the last two decades, and is defined as the control processes responsible for planning, assembling, coordinating, sequencing, and monitoring other cognitive operations (Salthouse, Atkinson, & Berish, 2003). According to Salthouse et al. (2003), this concept could provide information about adult age differences in cognitive functioning, since executive functioning encompasses concepts such as inhibition, working memory, and attentional capacity, which play a major role in theories of cognitive psychology. In drivers and pedestrians, for example, the ability to allocate attention – both focusing and shifting – to the relevant environmental cue/s is crucial in enabling them to process information effectively, and in turn to make appropriate decisions related to daily-life activities, such as driving and pedestrian acts (see Bäckman et al., 2010; West, 1996). In this respect, recording gaze behavior can help researchers understand *where* overt attention is directed, since it appears that the direction of gaze is linked to the individual's attention (Groner & Groner, 1989; Deubel & Schneider, 1996; Groner & Groner, 2000; Henderson, 2003; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986).

The relationships between gaze behavior and driving have been examined in a number of studies. For example, researchers studied eye-head coordination during driving (Land, 1992), visual scanning of experienced and novice young adult drivers (Falkmer & Gregersen, 2005; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), visual scanning in relation to various driving conditions (Konstantopoulos, Chapman, & Crundall, 2010), and visual scanning while driving under the influence of alcohol (Shiferaw, Stough, & Downey, 2014). Generally, it was found in all of these studies that gaze behavior can affect driving performance.

Since human aging is associated with a decline in various cognitive abilities (Bäckman et al., 2010; West, 1996), driving and crossing the road can be negatively influenced by this decline. In order to improve safety, evidence-based knowledge on how older individuals gaze during high-risk daily-life activities, such as driving and crossing the road, can be valuable to both researchers and practitioners. As far as we know, up to now no review articles exist on gaze behavior in older drivers and elderly pedestrians, and therefore in the current article we review a series of studies focusing on the effect of age on gaze behavior in this population. Based on this review, we (a) discuss and compare evidence-based knowledge about aging and gaze behavior in drivers and pedestrians, (b) discuss a number of methodological concerns and research limitations associated with the reviewed studies, and (c) propose a number of ideas for additional studies of gaze behavior in older drivers and pedestrians.

The evidence-based knowledge on aging and gaze behavior in drivers and pedestrians that emerged from the current review can assist researchers in their future work as well as those who aim at developing agendas and policies for the elderly driver and pedestrian populations. In addition, this evidence-based knowledge can be used by practitioners to develop better training programs aimed at improving the gaze behavior of older drivers and pedestrians.

Literature Search

An electronic search was conducted using three computerized databases: Google Scholar, SPORTDiscus, and PubMed. A combination of the following terms was used: *gaze behavior, eye movement, older age, older adults, street crossing, motor performance,* and *driving.* No time limit was set for the literature search. A manual search of the reference lists of the relevant articles was performed independently by the two authors as well. Inclusion criteria were: (a) studies published in peer-reviewed journals, (b) studies that had at least one group of older adults (age > 50 years) as participants, and (c) studies published in English. All the studies were assessed for inclusion by the first author of the current review, and then assessed independently by the second author.

The search yielded 25 studies, which are reviewed in the current article. Since this is the first review on the effect of age on gaze behavior in drivers and pedestrians, our aim was to include all the studies that focused on this issue and met the three above-mentioned inclusion criteria. Therefore, none of these studies were eliminated. We decided to conduct a qualitative review and not a systematic review or a review based on a meta-analysis approach, not only because this review is the first to consider the effect of age on gaze behavior in drivers and pedestrians, but also because the number of studies found was relatively small and the measured dependent variables in the reviewed studies differed among the studies.

Studies on the Effect of Age on Gaze Behavior in Drivers and Pedestrians

In general, it appears that age affects the gaze behavior of older drivers and pedestrians. For example, compared to younger drivers, older drivers appear to make fewer fixations on relevant locations in the visual field when changing lanes; older drivers also spend less time scanning to the left, to the right and for oncoming traffic when they approach an intersection. Older drivers' less-effective visual scan strategies are also related to poorer road perception. However, it appears that older drivers fixate better on possible risks, therefore compensating for their relatively poor visual scan patterns compared to younger drivers. Lastly, as pedestrians, older adults make longer glances at signals. Those fixations allow them to react in time to changes in the signals (e.g., change of the light from green to red). However, these longer fixations may prevent them from noticing other pedestrians, uneven pavement, or other obstacles.

The reviewed studies are presented in alphabetical order. We grouped the studies into five categories: lane changing, managing an intersection, road perception, risk perception, and pedestrians' gaze behavior. A summary of the studies examining these **issues** is presented in Table 1.

The eye-tracking methods and analysis varied between studies. Some of the studies used head-mounted eye-tracking systems, with a sampling rate of up to 60 Hz. Other studies used remote eye-tracking systems. In addition, several studies did not measure eye movements at all. Rather, they inferred gaze behavior based on head movements that were recorded with a simple external camera.

Lane Changing

It is often necessary for drivers to change lanes while driving. When changing lanes in order to overtake a slower vehicle, for example, the driver has to direct his or her attention to the rearview mirror, the left side mirror, and the blind spot between the visual fields that both mirrors provide. Failing to attend to what is seen in the mirrors and to the blind spot can lead to missing crucial visual information (e.g, the presence of another vehicle close by, or a vehicle closing in at a high speed).

We found three studies that examined the differences in gaze behavior between younger and older drivers when changing lanes (Lavallière, Laurendeau, Simoneau, & Teasdale, 2011; Lavallière et al., 2007; Lavallière, Tremblay, Cantin, Simoneau, & Teasdale, 2006). In two of these studies (Lavallière et al., 2011; Lavallière et al., 2007), older drivers did not glance as frequently as younger drivers at three important regions – the rearview mirror, the left side mirror, and the left blind spot. More specifically, while younger drivers inspected their rearview mirror 83% of the time before changing lanes, older drivers inspected them only 51% of the time. In addition, the blind spot was examined 85% of the time in young drivers compared to 41% in older drivers (Lavallière et al., 2011). As the authors of this study suggest, the less-than-optimal gaze behavior of older drivers can be modified by specific training. This, in turn, can lead to a reduced risk when changing lanes. In the third study (Lavallière et al., 2006), older drivers had a smaller horizontal gaze amplitude than younger drivers. This age-related perceptual narrowing (i.e., tunnel vision effect) can lead to reduced driving performance, especially when driving conditions are more challenging.

Lastly, one study examined the effects of receiving feedback on lane changing performance using a driving simulator (Lavallière, Simoneau, Tremblay, Laurendeau, & Teasdale, 2012). Compared to a control group (no training), three sessions of simulator driving with a feedback provision led to an increase in the frequency of inspection of the rearview mirror (from 32.3% to 64.9%). Importantly, the testing was conducted in on-road sessions. This finding suggests that simulator training can be ecologically valid and the benefits can be transferred to on-road driving performances.

Managing an Intersection

Bao and Boyle (2007) found that compared to middle-aged drivers (ages 35 to 35 years), older drivers (ages 65 to 80 years) appear to spend less time scanning for oncoming traffic as they approach an intersection from a rural road to an expressway when there is moderate or heavy traffic on the expressway. In addition, in higher traffic volume, the middle-aged drivers took more time to scan the intersection and wait for an appropriate gap in traffic before entering the intersection. In these circumstances, the less-than-optimal visual scanning performance of the older adults may contribute to poor decisions when entering the intersection and lead to an increased risk of accidents.

Age differences in visual scanning behavior were also found in other studies (e.g., Bao & Boyle, 2009; Dukic & Broberg, 2012; Scott, Hall, Litchfield, & Westwood, 2013). Bao and Boyle (2009) found that older adults (ages 65 to 80 years) scanned to the left and to the right for a shorter time than younger (ages 18 to 25 years) and middle-aged (ages 35 to 55 years) adults before entering an intersection in a rural area. In addition, both older and younger adult drivers scanned fewer areas of the intersection compared to middle-aged drivers. It should be noted that in the studies by Bao and Boyle (2007, 2009), visual scanning was examined using external cameras that recorded face views. The fact that eye-tracking equipment was not used in these studies is a major limitation, as vision can be directed to locations that are not in the direction to which the head is turned.

A study where eye movements were directly measured when participants made a right turn in a driving simulator showed that older drivers did not shift their gaze between regions of interest (e.g., far left, center, far right) as evenly as the younger drivers did (Scott et al., 2013). In addition, when getting ready to perform a turn, older drivers made fewer preview gazes towards the direction they were turning to. These data suggest that older drivers may not be as effective as younger drivers in scanning for traffic coming from the right to the left in an intersection.

Older drivers might also be at risk of causing an accident when entering a 4-way intersection and turning right. This is due to the fact that they spend less time scanning forward, and therefore they might miss a vehicle coming towards them and turning left onto the same lane (Min, Min, & Kim, 2013). However, since these drivers spend more time looking in the direction of the turn, they are more likely to stop in time if a car ahead of them suddenly stops or if a pedestrian enters a road crossing. Older drivers also drive slower than younger drivers when entering and exiting an intersection. Paradoxically, this can increase the risk for accidents, as it disturbs the natural flow of traffic.

Lastly, one study (Romoser & Fisher, 2009) examined the effect of active simulator training on increasing the likelihood that older adults will look at possible threats as they turn into an intersection. Indeed, active simulator training that included feedback increased the older drivers' likelihood of looking for possible threats by 100%. In contrast, a passive-classroom learning group and a control group (no training) showed no improvement in the likelihood of looking for threats on the road. Importantly, in a follow-up study after two years (Romoser, 2013), older drivers had maintained improved intersection scanning behavior. In this study, older drivers who participated in an active-driving learning two years previously looked more than 1.5 times as often as their pre-training levels to regions from which vehicles could appear. Therefore, it appears that older drivers can retain their training skills for long durations.

Road Perception

One study (Reimer, Mehler, Wang, & Coughlin, 2010) reported that when drivers from three age groups (young, middle-aged, and old) were required to perform a secondary task while driving, their horizontal gaze became more centralized as the task became harder. No differences were found between the three age groups. However, compared to young drivers, older drivers exhibited longer search durations and greater search variability when extracting the same information from a driving scene.

In another study, older drivers seemed to have lapses in their visual search. These lapses were characterized by a higher frequency of fixations and shorter saccades (Maltz & Shinar, 1999). As the authors of this study explained, it is not clear whether this sub-optimal gaze behavior is serious enough to categorize older drivers as poor drivers, since they can have compensating mechanisms that allow them to drive safely. In addition, the small sample size in this study (five per group) makes generalization impossible.

According to another study (Ho, Scialfa, Caird, & Graw, 2001), compared to young drivers, older drivers were slower to distinguish traffic signs, slower to realize that no sign is present, performed more fixations before finding the sign, and made more errors in sign identification. As a result, the time spent on locating signs was time not spent on checking other important objects in the driving scene (e.g., pedestrian crossings and oncoming traffic). Similar results were found in a study that used a dual-task paradigm in addition to a single-task one (McPhee, Scialfa, Dennis, Ho, & Caird, 2004). In this study, older adults were slower to find signs, made more errors in identifying signs, and were slower to determine whether a sign was or was not present at the scene. Under dual-task conditions (e.g, memory tests that require a conversation between the researcher and the participant), older adults exhibit longer fixations and a reduction in the performance of the memory test. The longer fixations and the cautiousness in determining that a sign is not present may interfere with the ability to extract valuable information from the driving scene (e.g., presence of pedestrians, other cars, and obstacles).

Lastly, older drivers had more glances of over two seconds off the road compared to young and middle-aged drivers during a 350 km drive (Wikman & Summala, 2005). The glances inside the car were performed in order to complete a secondary task that required them to look at the middle console of the car and to push buttons in an ascending order of numbers. During the longer duration of glances off the road, the car travelled longer distances. In addition, older drivers had larger lateral lane displacements when looking inside the vehicle compared to both young and middle-aged drivers. The poorer performance of older drivers was related to a decline in some cognitive tests, but was not related to vision parameters. However, while older drivers with a lower attentional capacity appeared to perform fewer fixations when managing a roundabout in one study (Sun, Xia, Falkmer, & Lee, 2016), another study found that increased cognitive workload (i.e., late digit-recall while driving) was related to horizontal gaze narrowing and reduced driving performances, similarly to young adults, middle-aged adults, and older adults (Reimer, Mehler, Wang, & Coughlin, 2012).

Risk Perception

When it comes to the perception of risky driving scenarios, results are mixed. In one study (Pradhan et al., 2005), older drivers fixated on the potential risk on the road 66% of the time, compared to 51% of time for young drivers, and 36% for novice drivers. These findings suggest that older drivers may compensate for their sub-optimal gaze behavior by their longer driving experience. Such experience helps them to identify risky situations early and therefore to avoid them. Another study (Borowsky, Shinar, & Oron-Gilad, 2010) showed similar results when participants were required to identify road hazards while watching videos of driving scenarios on a computer screen. Older-experienced (37.5 years of driving experience) and experienced (7.3 years of driving experience) drivers were better at hazard detection compared to younger and inexperienced (2.7 months of driving experience) drivers. In addition, when entering a T-intersection, older and experienced drivers had more fixations on the merging road compared to young and inexperienced drivers, who fixated more straight ahead and tended to ignore the merging road.

In contrast to the previous studies, Romoser, Pollatsek, Fisher, and Williams (2013) found that differences in scan patterns between older and younger drivers were mostly seen from two seconds before until one second after entering an intersection in a driving simulator. Compared to younger drivers, older drivers looked more often towards the direction the vehicle was headed, but looked much less often than younger drivers towards regions were hazards may appear.

Pedestrians' Gaze Behavior

Four studies were found on gaze behavior in pedestrians. According to one study (Bock, Brustio, & Borisova, 2015), older adults have longer glance duration at a pedestrian traffic light. Their fixation on the light lasts throughout the green phase, the amber phase, and the red phase. In contrast, younger adults gradually increase their glance duration as the green phase continues, thinking that a color change is about to occur. The longer glances of the older adults can enable them to better prepare to stop when the light turns red. However, these fixations may also prove disadvantageous, as they may prevent older adults from scanning the environment and noticing other pedestrians, uneven pavement, or other obstacles.

In a second study (Geruschat, Hassan, & Turano, 2003), similar fixation distributions were observed in young and older adults when they were standing at the curb and preparing to cross an intersection. It is true that this study compared only three young adults to nine older adults, however it provided insights into the impact of age-related cognitive decline on older pedestrians.

A third study of simulated street crossing showed that older pedestrians fixate more on the ground and pay less attention to traffic compared to younger pedestrians. This gaze behavior was related to more dangerous street behavior as evidenced by more accidents with vehicles and fewer missed opportunities to cross (Zito et al., 2015). In contrast, a fourth study performed in a simulator failed to report differences in gaze behavior between younger and older pedestrians. Street crossing behavior also did not differ between groups, except for one difficult scenario in which older pedestrians were involved in virtual crashes (Jäger, Nyffeler, Müri, Mosimann, & Nef, 2015).

Methodological Concerns, Research Limitations, and Suggestions for Additional Studies

Based on the reviewed studies dealing with age and gaze behavior in drivers and pedestrians, four methodological concerns and research limitations are discussed. These concerns should be taken into account by researchers in their attempts to design additional studies on the effect of age on gaze behavior in drivers and pedestrians.

Lack of Studies Using a Vision-in-Action Paradigm

A vision-in-action paradigm examines the interrelations between gaze and action, and has been used extensively in gaze behavior research (for a review, see Vickers, 2009). The aim of this paradigm is to determine whether specific types of gazes are related to specific actions. For example, while older and younger drivers may share similar fixations towards oncoming traffic, it is the timing of those fixations in relation to the actual current motor performance of driving the car that is crucial. By using this paradigm, researchers will be able to answer questions regarding the timing and duration of fixations, in relation to the actual stepping on the gas pedal or the brake pedal, or the turning of the steering wheel. Such information will allow them to better differentiate between older and younger drivers. In addition, if the older driver has compensatory mechanisms for his or her sub-optimal gaze behavior, then the use of such a paradigm will help identify them. Unfortunately, only one study in our review (Lavallière et al., 2011) examined gaze behavior in relation to performances of a motor action in older adults. However, there has been some additional research examining this topic in young adult drivers (e.g., Land & Lee, 1994; Otto, 2013).

Scarcity of Data on Gaze Behavior and Elderly Pedestrians

We found only four studies that examined gaze behavior in older pedestrians. This is unfortunate, as older pedestrians have a greater risk of being involved in accidents with a motor vehicle as they cross the street (e.g., Dunbar, 2012). According to the NHTSA (2014), in 2012 pedestrians over the age of 65 accounted for 20% of all pedestrian fatalities, while they made up only 14% of the country's population (NHTSA, 2014). Understanding gaze behavior in older adults would enable researchers to better identify patterns of behavior that contribute to the sub-optimal decision making of these pedestrians when crossing the street. Such knowledge could further allow both researchers and practitioners to develop gaze training for older adults, which has the potential to increase the likelihood of safe street crossing.

Lack of Intervention Studies

Out of the 25 reviewed studies, only two studies (Lavallière et al., 2012; Romoser & Fisher, 2009) examined the effectiveness of gaze training on driving behavior. While this is a good start, it is not enough to formulate an understanding of the effects of gaze training on road performance. Therefore, additional interventional studies that examine the influence of training in optimal gaze behavior on driving a motor vehicle are needed. In addition, apparently young drivers can be trained to scan for relevant information in order to reduce the risk of car accidents and improve their ability to anticipate road hazards (Pradhan, Pollatsek, Knodler, & Fisher, 2009). Since research suggests that training gaze behavior can lead to improved performance, it is plausible that such training could improve driving performance of older adults as well.

Lack of Studies on Emergency Situations

We found only one study that examined risk perception (Pradhan et al., 2005), and no studies that examined gaze behavior when dealing with an emergency situation (e.g., when another vehicle enters an intersection at a red light, requiring the driver to suddenly brake). It is possible that the benefits of optimal gaze behavior would be most noticeable under emergency conditions. Under such conditions, optimal gaze behavior can give drivers or pedestrians the needed extra time that will allow them to make a correct decision and avoid an accident. The use of advanced technology and simulators can assist researchers in mimicking other emergency situations for their future inquiries.

Implications for Research and Practice

The data that emerged from the studies on lane changing, managing intersections, road perception, risk perception, and pedestrians' gaze behavior provide us with relevant information on what differentiates young drivers/pedestrians from their older counterparts. Taking into consideration the data on the deterioration in cognitive abilities (e.g., attention, memory) and executive functioning in the elderly population (e.g., Bäckman et al., 2010;

Salthouse et al., 2003), it is apparent that task-specific training programs aimed at improving gaze behavior in this population are needed. Unfortunately, only a few experiments have examined the effectiveness of such programs on gaze behavior in older drivers, and particularly in older pedestrians. We propose that additional studies focusing on how to teach older drivers and pedestrians optimal gaze behavior should be performed, in order to enable members of this population to function better when driving a motor vehicle or crossing the road. These future studies should attempt to incorporate modern eye-tracking technologies. Eye-tracking devices that have a faster sampling rate (i.e., > 120 Hz), are more accurate, and can be wireless. Using such technologies can lead to a better understanding of the effects of training for optimal gaze behavior on the performance of drivers and pedestrians.

Importantly, older pedestrians make more errors when crossing streets, and older drivers are less observant when driving their cars. Therefore, the interaction between older drivers and older pedestrians presents the greatest risks, especially for the pedestrians. Educational and training agencies should take this observation into account when teaching road safety to older drivers and older pedestrians. Explaining the decline in performance to older adults and teaching them how to take extra precautions when driving or crossing streets can be useful in preventing accidents.

Future work should also examine the neuropsychological mechanisms underpinning older drivers' gaze behavior. Research should also be conducted on older adults with age-related cognitive disease (e.g., post-stroke, Parkinson's disease). Such research should strive towards more sensitive quantitative measurements on gaze behavior as well. Lastly, efforts should be made to increase the benefits gained from the available advanced technology and simulators in order to mimic authentic, real-life conditions where researchers can enhance their studies on risk perception in older drivers and pedestrians.

Conclusions

Three conclusions can be made based on the current review. First, it appears that age affects gaze behavior of older drivers and pedestrians (e.g., performing fewer fixations to relevant locations in the visual field when changing lanes). Second, since gaze behavior appears to be related to driving performances and to pedestrians' ability to cross streets, it can play an important role in the safety of older drivers and pedestrians. Third, additional studies on various aspects of gaze behavior in older individuals are needed, among them the neuropsychological mechanisms underpinning older drivers' gaze behavior as well as the effectiveness of task-specific training programs aimed at improving gaze behavior in this population.

The three conclusions that stem from this review suggest that the gaze behavior of older adults on the road should continue to be an active field of research, as it can affect road safety and performance in a large portion of the human population.

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Table 1

A Summary of Studies (N = 23) Examining the Effect of Age on Gaze Behavior in Drivers and Pedestrians (the studies are presented in alphabetical order).

Study	Participants	Method and Tasks	Measures and Technology	Results
Bao & Boyle (2007)	MA: 35-55 (n=10) O: 65-80 (n=10) 5 females and 5 males in each group	Driving through two rural median-divided highway intersections: high crash rate or low crash rate Three driving maneuvers: left turn and right turn (from rural to expressway), and straight across the intersection Cameras to examine face views	Number of eye glances to left and right Search duration (time between starting point to 34 meters before stop sign) No use of eye-tracking technology. Coding visual search from video of participants' face and head movements	Left and right eye glances: MA = O. Search duration: Search for opposing traffic: O < MA In moderate- and high-volume traffic: Time observing traffic before entering intersection: MA > O
Bao & Boyle (2009)	Y: 18-25 (n=20) MA: 35-55 (n=20) O: 65-80 (n=20) 10 females and 10 males in each group	Same as in Bau & Boyle's (2007) study	Visual scanning Location Proportion of scanning Randomness of scanning No use of eye-tracking technology	Visual scanning to left and right during intersection negotiation: O < Y, MA O focused more on one traffic stream before right or left turn Glances toward turning directions: O < Y, MA Scanning all areas: MA > Y,O Checking rearview mirror: MA > Y, O
Bock et al. (2015)	Y: 20-30 (n=17, 8 females) O: 60-80 (n=16, 6 females)	Moving through a three- dimensional virtual reality shopping district placed around on a treadmill Responding to change of traffic light from green to red requiring participants to stop. 30 events in a session with a maximum duration of 8 min	Total gaze time Number of glances Mean glance duration Eye tracking with a 30 Hz head-mounted system	Mean glance duration at traffic light: O > Y Sum of all glances: O > Y O looked at the traffic light throughout green, amber, and red Y increased inspection of the green light as it went on and the likelihood of a color change increased
Borowsky et al. (2010)	Y and inexperienced: 17-18 (n=21) Y and experienced: 22-30 (n=19) O and experienced: 65-72 (n=16)	Identifying hazardous driving situations while sitting in front of a computer screen and watching videos from the driver's perspective	Gaze behavior Road hazard detection Eye tracking with a 50 Hz remote system	Hazard detection: O and experienced, Y and experienced > Y and inexperienced Fixation towards merging road in T intersection: O and experienced, Y and experienced > Y and inexperienced
Dukic & Broberg (2012)	Y: 25-55 (n=53, 10 females) O: >75 (n=26, 9 females)	Driving through routes with different speed limits and different types of intersections	Neck flexibility Gaze behavior Head rotations Speed of vehicle Eye tracking with a 50 Hz head-mounted system. Raw data reviewed for quality	Neck flexibility: Y > O. First gaze to left or right before intersection: Y before O Fixation duration: O > Y Gaze distribution: Looking straight ahead and looking at lines and markings: O > Y Looking at other cars: O < Y
Geruschat et al. (2003)	Y: mean age = 27.7 (n=3) O: mean age = 72.2 (n=9)	Crossing two types of intersections	Gaze behavior Head position Eye tracking with a head-mounted system. Sampling rate not reported	Fixations' distribution while standing at the curb are similar between Y and O

Ho et al. (2001)	Y: 18-30 (n=14) O: 54-79 (n=14)	Searching for traffic signs (presence or absence) in day and night digitized scene images with low and high visual clutter Two blocks of 25 trials	Gaze behavior Correct identification of presence or absence of sign Eye tracking with a 30 Hz remote system	Accuracy of sign identification: O < Y (especially in absence trials) Search efficiency: O < Y Search duration: O > Y # of fixations to acquire the sign: O > Y
Jäger et al. (2015)	Y: 25-37 (n=15) O: 63-86 (n=15) S: various ages (n=5)	Crossing a two-way road in a simulator	Decision to cross Gaze behavior Missed opportunities Virtual crashes Eye tracking with a head-mounted system Sampling rate not reported	Virtual crashes: Y = O Missed opportunities: Y < O (trend towards sig.) Most difficult scenario: Crashes and missed opportunities: O > Y Gaze behavior: O = Y
Lavallière et al. (2006)	Y: 20-31 (n=10) O: 65-75 (n=10)	26.4 km route of urban and rural roads in a driving simulator. Six open road sections, 15 intersections, 5 passing maneuvers	Gaze behavior Eye tracking with a 60 Hz remote system that includes a head tracking device as well	Driving performance: 1 accident by an older driver who failed to look at a stop light # of fixations/sec in complex driving maneuvers: O < Y Horizontal gaze amplitude: O < Y
Lavallière et al. (2007)	Y: 20-24 (n=12) O: 66-75 (n=11)	Changing lanes driving scenario in a driving simulator that includes 16 events requiring looking at rearview mirror, left side mirror, and left blind spot	Head movements and gazes to ROI: rearview mirror, left side mirror, left blind spot No use of eye-tracking technology. Head movements recorded at 60 Hz. Measured glances to three ROI's	Frequency of visual inspection of rearview mirror and blind spot: O < Y Frequency of inspection ROI when passing a slower vehicle: Y > O
Lavallière et al. (2011)	Y: 21-31 (n=10, 4 females) O: 65–75 (n=11, males)	Same as in Lavallière's (2007) study	Same as in Lavallière's (2007) study	Frequency of visual inspection of rearview mirror and blind spot: O < Y Frequency of inspection ROI when passing a slower vehicle: Y > O Control of vehicle: O = Y
Lavallière et al. (2012)	Older drivers (65-85) E: n=10, 4 females C: n=12, 3 females	Driving simulator with video-based feedback Changing lanes in an urban environment On-road driving evaluation before and after three simulator sessions: E: driving simulator with feedback about their previous session C: driving simulator with no feedback	Neck range of motion Frequency of inspections to five ROI: forward, odometer, rearview mirror, external mirrors, blind spots No use of eye-tracking technology. Head movements recorded at 60 Hz	After simulator and feedback training: Inspection frequency of blind spot increased in E (by 100%) but not C group
Maltz & Shinar (1999)	Y: 20-30 (n=5) O: 62-80 (n=5)	Six digitized images of traffic scenes In two images participants were required to find the numbers 1-14 which were scattered randomly In four images, participants were required to look at important information for safe driving	Search times Fixations In the numerical images Number reached in 10 seconds (from 1-14) Eye tracking with a 60 Hz head-mounted system	Search times to extract same information: O > Y Variability in search data: O > Y Lapses in search with increased # of fixations and shorter saccades in older adults
McPhee et al.	Y: 17-33 (n=16, 11	Searching for traffic signs in digitized images	Errors in identifying signs	Sign identification accuracy: O< Y

(2004)	females) O: 56-71 (n=16, 7 fe-males)	with high or low clutter Single-task or dual-task (memory test) conditions	Number and duration of fixations Memory scores Eye tracking with a remote system. Head secured chin rest and forehead rest. Sampling rate not reported	Especially in high-clutter scenes Time to decide sign is not present: O > Y Fixation duration in dual task: O > Y Memory scores: O < Y
Min et al. (2013)	Y: 20-30 (n=18) O: >65 (n=21)	Two 10-min driving scenarios in a simulator. Two turn types and 3 intersection types appeared 4 times	Driving behavior Gaze behavior. Eye tracking with a head-mounted system. Sampling rate not reported	Right turn: Scanning forward: O < Y Scanning to right: O > Y Velocity when entering or exiting intersection: O < Y
Pradhan et al. (2005)	N: 16-17, < 6-months driving experience (n=24) Y: 19-29 (n=24) O: 60-75 (n=24)	Driving through 16 risky scenarios in a driving simulator Four blocks of 4 scenarios	Safe or unsafe behavior Eye movements Eye tracking with a 60 Hz head-mounted system	Fixating on the potential risk: O > Y > N In all 16 scenarios: O > N In 14 of 16 scenarios: O > Y
Reimer et al. (2010)	Y: 20-29 (n=36) MA: 40-49 (n=36) O: 60-69 (n=36)	Actual driving with low, moderate, and high secondary cognitive workloads 30 min warm-up, 2 min single task, four 30-sec trials with secondary tasks	Gaze behavior Secondary task performance Driving speed Eye tracking with a 60 Hz remote system	Secondary task performance and driving speed: O < Y, MA Horizontal gaze centralization in all age groups with increasing cognitive workload
Reimer et al. (2012)	Y: 20-29 (n=36) MA: 40-49 (n=36) O: 60-69 (n=36)	Actual driving while performing a secondary task of delayed digit-recall (3 difficulties)	Gaze behavior Secondary task performance Driving performance Eye tracking with a 60 Hz remote system	Increase gaze concentration with increased secondary task difficulty in all age groups Trend for inverse relationship between gaze concentration and performance scores
Romoser & Fisher (2009)	Exp 1: Y: 22-55 (n=18) O: 72-87 (n=18) Exp 2: O1: 70-74 (n=18) O2: 75-59 (n=18) O3: 80-89 (n=18)	Exp 1: Ten driving simulator scenarios (8 of them of turning in intersections) with risky elements appearing in the driving scene Exp 2: Three groups: (1) active: 6 sessions of secondary-look training in simulator and in the field with intersection behavior feedback, (2) passive-classroom training, (3) C (no-training)	Exp 1 & 2: Errors made Primary looks (scanning before executing a turn) Secondary looks (scanning while performing a turn). Eye tracking with a 60 Hz head-mounted system	Exp 1: Secondary looks: O < Y. Turn too slow: O > Y. Exp 2: Probability of looking at threat during turn increased for active group, but not for passive or control group
Romoser (2013)	Same as Romoser & Fisher (2009)	A two-year follow-up of Romoser & Fisher's (2009) study	Secondary looks follow-up study. No actual eye tracking performed	Those who participated in active driving learning looked more than 1.5 times as often as their pre-training levels towards areas from which vehicles could appear, even after two years
Romoser et al. (2013)	Same as Romoser & Fisher (2009)	Following a lead car in three intersection scenarios: (1) turning left across incoming traffic at four-way intersection, (2) turning right from a stop at a T-intersection, (3) going straight through a four-way intersection with two-way stop	Gaze behavior from 8 seconds before to 5 seconds after entering the intersection. Eye tracking with a 60 Hz head-mounted system	Major differences between O and Y from 2 seconds before to 1 second after entering the intersection Left turn across traffic: glancing to central region: Y > O Fixating to direction of travel: Y < O Right turn at T-intersection Looking to far left: Y > O Looking to near right (direction of turn): Y < O Straight through intersection:

				Glancing far right and far left: Y > O Looking to center zone (direction of travel): Y < O
Scott et al. (2013)	N: mean age 20.6 (n=14) Y: mean age 23.8 (n=14) O: mean age 66.4 (n=14)	Performing a right turn in a driving simulator	Gaze transitions between 7 ROI Initial scanning phase (first 10 seconds of scenario) Decision phase – from 5 seconds before initiating turn Eye tracking with a head-mounted system. Sampling rate not reported	Scanning phase: Y – Distributed gaze more evenly across ROI compared to N and O Decision phase: Preview gazes towards the road far ahead: O < N, Y
Sun et al. (2016)	Drivers between the ages of 60-80 (n=30)	16 driving scenarios including right and left turns, roundabouts, and straight road driving	Five fixation parameters Vehicle trajectory Eye tracking with a 60 Hz head-mounted system	Fixation frequency: turn and roundabouts > straight road Lower capacity of attention was related to less frequent fixations at roundabouts
Wikman & Summala (2005)	Y: 20-24 (n=10) MA: 26-44 (n=9) O: 57-73 (n=11)	Driving 350 km while performing two secondary tasks: (1) pushing buttons in ascending order from 1 to 8 on a digit display located in the middle console, (2) reading the numbers from top left to bottom right	Gaze transitions from inside the car to out the window Cognitive tests Driving performance No use of eye-tracking technology. Recording glances based on a camera videotaping the face of the participant	During pushing the keys task: Time and distance car travelled when looking off the road: O > Y, MA Glances of <2 sec off the road: O > Y, MA (large variance in O group) Lateral displacement of car: O > Y, MA
Zito et al. (2015)	Y: 23-28 (n=18) O: 65-79 (n=18)	Crossing a two-way road in a simulator Scenarios with vehicles travelling at 30 or 50 km/h Choosing whether the gap between cars is long enough to cross the street	Safe crosses Virtual crashes missed opportunities Gaze fixations to three ROI Head movements Eye tracking with a head-mounted system Sampling rate not reported	Fixations to ground: O>Y Fixations to other side of street to cross: O<Y Fixations to right side: O<Y # of virtual crashes: O>Y # of missed opportunities: O<Y

Note: Y = young; MA = middle age; O = old; N = novice; E = experimental group; C = control group; S = stroke patients with impaired vision; ROI = regions of interest