The effects of visibility conditions, traffic density, and navigational challenge on speed compensation and driving performance in older adults

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Article info

Article history:
Received 25 August 2009
Received in revised form 28 February 2010
Accepted 8 April 2010

Keywords:
Older drivers
Visibility
Wayfinding
Traffic density
Workload
Speed compensation

Abstract

Research on how older drivers react to natural challenges in the driving environment is relevant for both the research on mental workload and that on age-related compensation. Older adults (M age = 70.8 years) were tested in a driving simulator to assess the impact of three driving challenges: a visibility challenge (clear day, fog), a traffic density challenge (low density, high density) and a navigational challenge (participants followed the road to arrive at their destination, participants had to use signs and landmarks). The three challenge manipulations induced different compensatory speed adjustments. This complicated interpretation of the other measures of driving performance. As a result, speed adjustment indices were calculated for each condition and participant and composite measures of performance were created to correct for speed compensation. (These speed adjustment indices correlated with vision test scores and subscales of the Useful Field of View®.) When the composite measures of driving performance were analyzed, visibility × density × navigational challenge interactions emerged for hazard RT and SD of lane position. Effects were synergistic: the impact of the interaction of challenge variables was greater than the sum of independent effects. The directions of the effects varied on the performance measure in question though. For hazard RT, the combined effects of high-density traffic and navigational challenge were more deleterious in good visibility conditions than in fog. For or SD of lane position, the opposite pattern emerged: combined effects of high-density traffic and navigational challenge were more deleterious in fog than in clear weather. This suggests different aspects of driving performance tap different resources.

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1. Introduction

Older drivers are disproportionately at risk for certain types of collision (e.g., McGwin and Brown, 1999; Preusser et al., 1998) and are more likely to die or sustain serious injury as a result (Hauer, 1988; Skyving et al., 2009). The goal of this study was to investigate the impact of challenges inherent in different types of drive by manipulating these factors and measuring their effects, singly and in combination, using a driving simulator. This represents a different approach to the study of mental workload in older drivers insofar as it does not require secondary tasks that are not a natural part of driving. Information about the interactive effects of different types of challenge are informative in light of discussions about whether different challenges draw on the same resource or if there are different resources for different challenges. As well, given that the introduction of driving challenges may induce drivers to compensate by slowing down, and given that the degree of compensatory slowing may be related to individual capacities, this work may be relevant to theories of age-related compensatory behaviors (Baltes, 1997; Brouwer et al., 1988).

Age and age-related disorders are associated with a variety of changes in sensory, motor and cognitive function (e.g., Scialfa and Kline, 2007; Spirduso et al., 2003; Kramer and Kray, 2006; Park and Payer, 2006; Zacks and Hasher, 2006). Some of these changes result in performance deficits, though these deficits are more notable in some domains than others. In particular, there are a variety of studies that suggest that though an individual’s overall store of knowledge (their crystallized intelligence) may be stable or even increase with age, performance tends to decline in tasks that require fluid intelligence: tasks that make extensive demands on executive working memory and attention (see Li et al., 2009 for a review). It has been suggested that age-related neural pathology and demyelination produce deficits in both processing speed and performance stability across time (“robustness”), and the effects are especially noticeable in complex perceptual motor tasks (Li et al., 2004; MacDonald et al., 2009). One such task is driving an automobile. Driving requires rapid response and the ability to carry out several activities at once, such as monitoring for hazards while steering and controlling the speed of the vehicle. Thus, even though...
many older drivers have decades of driving experience, they may begin to miss important safety-related information in complex, challenging driving environments (e.g., unfamiliar roads, information rich areas such as intersections, e.g. McGwin and Brown, 1999; Preusser et al., 1998). The importance of attention is borne out by the observation that attentional measures are the best predictors of driving performance in older drivers (e.g. Ball et al., 1993; Mathias and Lucas, 2009) and this has inspired research on the impact of attentional demands on performance in older drivers. A large number of these studies reflect the impact of Shiffrin and Schneider’s (1977) seminal paper on automatic and controlled processing. Shiffrin and Schneider proposed that although there are many types of mental process (perceptual, motor, memory), all fall into one of two categories. Automatic processes occur without awareness or intent and they can be carried out concurrently with other processes without compromising performance. In contrast, controlled processes occur with awareness, and are deliberate and goal oriented. These processes are effortful and slow and it is difficult to carry out several controlled processes at once. These are said to be attention-demanding: they produce “cognitive load”. When two controlled processes are carried out at the same time, there is interference, which is to say, performance is worse on one or both tasks when the tasks are performed together than when they are performed separately because they share a common limited capacity resource.

Perhaps because of the influence of this theory, although there are many techniques for measuring workload (Verwey and Veltman, 1996), the most common way to investigate age-differences in attention is to use the dual task paradigm. Often these studies look at how adding secondary tasks interferes with driving, and there are a variety of such secondary tasks, including carrying out mental arithmetic, scanning in-vehicle displays or the immediate environment for certain probe stimuli, answering questions or engaging in conversations (e.g., Cantin et al., 2009; Pohlmann and Traenkle, 1994; Shinar et al., 2005; Verwey, 2000; Zeitlan, 1995). Some of these studies also manipulate the complexity of the drive insofar as they compare rural and urban driving (e.g. Cantin et al., 2009), low and high-density traffic (Cnossen et al., 2004; Verwey, 2000), familiar versus unfamiliar settings (e.g. Verwey, 2000), etc. Nonetheless, the focus is always on the dual task manipulation: the amount of interference produced by carrying out two tasks once. Effect magnitudes vary, but most studies show more dual task interference in older than younger drivers and these results have been interpreted as evidence that older adults have fewer resources for controlled processing (see also Riby et al., 2004). At present, most of the debate centres around whether there is a single limited capacity resource or different resources for different task modalities (e.g. Resource theory: Kahneman, 1973; Multiple Resource theory: Wickens, 2002 respectively).

The dual task paradigm has been and will continue to be very useful. However, it has drawbacks that may, at times, limit the validity and generality of the findings. For one, when a novel secondary task is introduced, participants first have to learn how to carry out the secondary task before they can combine it with driving. Older adults may take longer to learn how to perform the secondary task and as a result, when their performance suffers it may be because they have not had enough time to learn the secondary task whereas the younger adults have. Furthermore, even if the secondary task per se is not novel, the combination of tasks may be. Many dual task studies require putting together tasks that typically do not go together, at least for older drivers. For example, a number of studies use mental arithmetic as the chosen secondary task. This task generates substantial amounts of interference (e.g., Makishita and Matsumaga, 2008; Shinar et al., 2005) but most people do not carry out mathematical calculations while driving. Consequently, when older drivers show more interference between tasks, it is unclear whether it is because older drivers have fewer resources for controlled processing or because older drivers have special difficulties with peculiar combinations of tasks (see McDowd and Craik, 1988 for a discussion). In addition, whenever dual task studies are carried out, there is a danger that individuals vary in the emphasis they give to one task as opposed to the other. Cnossen et al. (2004) found that when the secondary task was not intrinsic to driving, drivers put less emphasis on it. This may be especially true for older adults, who may compensate for age-related deficits by de-emphasizing the non-driving related secondary tasks in the interests of safety (see Baltes, 1997; also Li et al., 2001). This underlines the importance of measuring both driving and secondary task performance in dual task studies that test older drivers. If the focus is solely on driving performance, it is possible that the study will underestimate the true costs of multi-tasking.

In this study we tried a more naturalistic approach, exploiting the fact that the driving task involves many different types of load that may interact in interesting ways. We explored three types of driving challenge: visibility challenges, traffic density challenges, navigational challenges. These challenges were chosen to cover a spectrum ranging from challenges that were more sensory (the visibility manipulation) to those that were more attentional and memorial (the traffic density and wayfinding manipulations). The visibility manipulation involved comparing driving in (simulated) fog with driving in (simulated) clear weather. Collision risk increases in fog and even professional drivers find driving in fog stressful (Vivoli et al., 1993). Fog reduces image contrast. This impairs distance perception, which can prompt rear end collisions (Broughton et al., 2007; Buchner et al., 2006; Cavalli et al., 2001). It also causes drivers to underestimate how rapidly other vehicles are traveling (Horswill and Plooy, 2008; Snowden et al., 1998). Furthermore, because objects have to be closer to become fully visible, fog reduces the amount of time drivers have to react to stimuli in the environment. Given that age is associated with reductions in contrast sensitivity (Scafia and Kline, 2007) and increases in response time even in well-practiced tasks (Voelcker-Rehage and Alberts, 2007), fog should be especially problematic for older drivers. Nonetheless, there is little research on how older drivers perform when they drive in fog.

Traffic density is also a factor in collision risk and increased traffic affects performance even in professional drivers (Hanowski et al., 2009). For some drivers, high-density traffic provokes anger and aggression (Parker et al., 2002), though this may be partly because it increases physiological arousal, an effect that can be beneficial for those with a tendency to doze off while driving (Tassi et al., 2008). In this study, the amount of oncoming traffic was manipulated. Although the oncoming traffic did not venture into the driver’s path it did serve as a source of dynamic visual clutter (see Horberry et al., 2006). Clutter increases demands on selective attention: the ability to select relevant items from irrelevant ones in the visual scene. Consequently, it interferes with the perception of signs and hazards. There is evidence that visual clutter is especially problematic for older drivers (McPhee et al., 2004; Horberry et al., 2006). The third challenge variable was wayfinding – the ability to navigate while driving. Compared to younger drivers, older drivers have more difficulties in finding their way to specific destinations and this can be a source of stress and embarrassment (Burns, 1998). At present, most of the wayfinding literature focuses on whether using an in-vehicle navigation system interferes with driving (Arbesman and Pellerito, 2008; Ma and Kaber, 2007). However, even without in-vehicle technology, wayfinding constitutes a secondary task that may compromise driving performance. This may be particularly true when wayfinding involves using a map (Cnossen et al., 2004; Lee and Cheng, 2008) but a recent study suggests that even talking about spatial navigation is enough to impair distance estimation (Patrick and Elias, 2009). In the present study, there were...
no in-vehicle navigation systems, maps, or spatial conversations. Instead, the wayfinding task required drivers to follow directions that they had committed to memory at the beginning of the trip. Even this simple wayfinding task requires multiple action monitoring (which puts demands on executive working memory) and divided attention insofar as it requires coordinating different tasks: driving, holding directions in working memory and using the directions at the appropriate time. It also requires selective attention insofar as following the directions would require drivers to search for relevant signs and landmarks in visual clutter. Consequently the prediction was that wayfinding would interfere with driving.

A sample of healthy, active older adults was tested in order to assess the effects of these challenge variables alone and in combination. In particular, the interest was in the combined effects of these variables because it is relevant to the question of whether different driving challenges all tax a common resource, or whether these challenges tax different resources. Thus, the interactive effects of these variables were assessed using common measures of driving performance: collisions, hazard RT, and standard deviation of lane position. As well, in conditions where drivers were required to use signs and landmarks to find their way, wayfinding errors (missed or extra turns) were measured. There has never been a study looking at the combined effects of visibility, traffic density, and navigational challenge, but there is a theory that might predict interactive effects: Baldwin’s sensory–cognitive interaction theory (2002). According to this theory, cognitive resources are used to order to compensate for low quality sensory information. Thus, there is reason to expect that sensory challenge (such as fog) would serve to exaggerate the effects of other cognitive challenges, including the traffic density challenge (visual clutter puts demands on selective attention), and the navigational challenge, which requires multi-tasking (driving while keeping information in working memory and searching for signs and landmarks).

Although there was reason to expect changes in performance as a function of the different types of driving challenge, there was also reason to expect that older drivers would reduce their driving speed to try to alleviate the effects of the challenges. An important component of tactical behavior is the ability to modify speed to match the conditions on the road (Summala, 1996). Drivers change their speed in response to the perceived risk of the drive (Fuller et al., 2008), increasing speed when they feel safe (e.g., Assum et al., 1999; Stanton and Pinto, 2000), or reducing it when they perceive increased risk, as sometimes occurs when people drive while using cellular phones (e.g. Haigney et al., 2000). It has been suggested that in general, older drivers adopt slower speeds to compensate for age-related increases in response time (Chu, 1994). If older drivers decrease their driving speed, and this adjustment is in fact successful in reducing these risks, it is possible that simple measures of driving performance may underestimate the true impacts of the challenge variables.

The presence of compensatory adjustments in speed complicates the interpretation of the other measures of driving performance insofar as the compensatory adjustments may effectively negate the impact of challenge variables. There are a number of approaches to this problem. One is to require drivers to maintain a constant speed regardless of challenge condition. However, this might contribute to stress in older drivers, many of whom were very concerned about their performance. Moreover, forcing drivers to go faster than they normally would (automatically) might constitute another secondary task that requires additional attentional resources. Another approach is to allow the older drivers to change speed as they see fit, and then measure the differences in speed and use it to create individualized indices of speed adjustment for each challenge. These individualized indices of adjustment could then be used to create composite measures of driving performance that factor in both speed and driving performance for each driver. This approach (the creation of composite measures) has been used to deal with speed-accuracy tradeoffs in other tasks (e.g., Akhtar and Enns, 1989).

These indices of speed adjustment were interesting in their own right. The ability to adjust speed appropriately in the face of difficult driving conditions is an important component of driver competence (de Craen et al., 2008) and there are concerns that deficits in cognitive status may reduce the amount of compensatory adjustment (Lundqvist and Alinder, 2007). In contrast, in community samples where there is no reason to expect marked deficits in cognitive status, it is possible that drivers with reduced sensory or attentional function may compensate more than other drivers if they have a reasonably good understanding of their own strengths and weaknesses. For example, drivers with deficits in contrast sensitivity may reduce their speed more for fog; drivers with difficulties in divided attention may reduce their speeds more in situations where they have to perform two tasks at once (wayfinding while driving). This pattern of results would be predicted by Baltes’ (1997) Selection, Optimization, Compensation theory of lifespan development, which suggests in the face of age-related deficits older adults optimize their performance, compensating for their losses (loss-based compensation), in this case, by adjusting their driving speed. Thus, although this study was primarily designed to investigate average differences in performance across challenge conditions, exploratory analyses were carried out to investigate whether individual differences in sensory or attentional function (as measured by common tests of acuity and attention) predict speed compensation.

2. Materials and methods

2.1. Apparatus and driving scenarios

A DriveSafety DS-600c simulator was used for testing: a 4-door sedan surrounded by 5 viewing screens to provide a 250° wrap-around virtual driving environment (5–50° screens enclosing the front and sides of the vehicle). Each simulated drive involved traversing a two-lane road through the country, past hills, trees, farms, and large buildings of various sorts (schools, fire halls, service stations). The speed limit was 80 kph, with speed postings appearing every 200 m. Eight different drives were created. These drives differed in scenery but they were approximately the same length and involved the same number of hazards and turns. The visibility and traffic density conditions were counterbalanced so each drive was carried out in every combination of conditions.

Three factors were manipulated to assess the influence of load in the drive. Visibility was manipulated by comparing driving on a clear day (items always visible within the line of sight) with driving in simulated fog (objects were obscured by fog if they were more than 600 m away). Traffic density was manipulated by comparing performance when there was roughly one oncoming car per every 1500 m (low density) to one every 150 m (high density). The oncoming traffic remained in its lane and there was no need for drivers to switch lanes (the vehicles driving ahead of the driver were far enough away that there was no need to pass).

The wayfinding manipulation involved comparing performance when participants simply had to follow the road to arrive at their destination (there were turns and intersections but all paths but the correct one were blocked off) to when drivers had to navigate from directions. At the beginning of the drive, participants were given the name of a specific town (e.g. “Kimball”) and they were given instructions on how to get there. These instructions told them to turn left (or right) at a certain landmark (e.g., a service station) and the landmark was shown to them on the screen. They were also told to turn left (or right) as indicated by a sign
that they would see on their journey (There were also distractor signs that directed drivers to destinations other than the specified target destination.). The wayfinding drive involved eight choice points, six of which were distractors where no turn was required. On half of the wayfinding drives the sign appeared first and on half of the drives the landmark appeared first. The maximum number of missed turns per drive was two, and the second turn occurred during the last 3–5 min of the 15-min drive. If drivers missed a turn they continued driving and a short interval down the road there was a forced turn (a turn with no choice point) that put them back on the correct path and they resumed the drive at the point after the turn (Error feedback was not given.). To our knowledge, this type of navigational task has never been used before and consequently the procedure was developed through pilot testing.

Five dependent variables were measured. Driving speed was assessed over 400 m segments of the road where there were no hazards, turns, landmarks or directional signs. The other four measures assessed driving performance. Of these, two were indices of hazard response: collisions and hazard RT. The hazards (dogs, cyclists, or vehicles) emerged suddenly from the periphery and came into the driver’s path (six hazards per drive). The hazard appeared 3.5 s in advance of a collision, or 78 m given the posted speed limit (80 kph). Collisions were defined as instances where the driver’s vehicle came into contact with an object on the road. Hazard RT was calculated as the time between the first appearance of the hazard and when braking occurred. The SD of lane position was assessed on straight, hazard-free segments of the road, where there were no turns, landmarks, or signs. Wayfinding performance was measured by assessing two types of navigational errors: errors of omission (i.e., number of times participants failed to make the appropriate turn in response to a sign or landmark) and errors of commission (the number of times participants turned at an intersection where they did not have to turn).

2.2. Participants

Thirty-four healthy active older drivers were recruited from a seniors’ recreational centre. Because older adults are especially at risk for simulator sickness (e.g., Caird et al., 2007) a two-stage screening process was used to ensure that all participants could make it through all eight experimental drives. First, each potential participant did the Simulator Sickness Questionnaire (Kennedy et al., 1983), and if they passed they were then given two 5-min tests in the simulator where they experienced turns and stops (These also served as training drives.). Fifteen recruits were judged at risk given this two-stage screening and were dropped before the study began (44% of the recruits: a value in line with other estimates for the prevalence of simulator sickness in older adults in simulations that involve multiple turns and stops, Trick and Caird, in press). Perhaps because of this rigorous screening, there was no evidence of simulator sickness during the experiment. The 19 remaining drivers made it through the eight experimental drives without incident. Their mean age was 70.8 years (SD = 5.98 years; 8 females), and all reported driving regularly, both in terms of the amount of time spent per day (M = 62.6 min, SD = 40.9), and the distance per day (M = 68.7 km, SD = 43.6).

Psychological tests were employed to describe this sample. The Mini-Mental State Exam (MMSE: Folstein et al., 1975) was included because it is one of the most commonly used measures of cognitive status, one that is frequently included in screening inventories (see Mathias and Lucas, 2009). For the 19 participants who made it through screening, the average MMSE score was M = 28.7 (SD = 1.1). Two common tests of visual sensitivity were also used: the Ferris et al. (1982) Early Treatment of Diabetic Retinopathy Scale (ETDRS) and the Pelli–Robson Contrast Sensitivity test (PR: Pelli et al., 1988).

In this sample, the average scores were LogMarr: M = .10 (SD = .11) for the ETDRS and M = 1.45 (SD = .07) for the PR. Participants were also tested with the Ball et al. (1993) Useful Field of View test (UFOV®), one of the best predictors of driving performance in older drivers (Ball et al., 1993; Mathias and Lucas, 2009). For the three subscales of the UFOV, the scores were as follows: perceptual speed (PS: M = 41.6, SD = 66.7), selective attention (SA: M = 106.4, SD = 106.7) and divided attention (DA: M = 189.2, SD = 80.3).

2.3. Procedure

To encompass this 2 × 2 × 2 design, there were eight – 15 min experimental drives. These drives were carried out on two consecutive days (total time required for the study, including surveys and tests: 3.5 h). The order in which drivers experienced the drives was counterbalanced so that every condition was in each position of the sequence of drives. All psychological tests were administered in the first session.

3. Results

The analyses involved three stages. First the raw data were analyzed. Repeated measures factorial analyses of variance were performed. Driving speed, collisions, hazard RT and SD of lane position were measured as a function of visibility (clear day, fog), traffic density (low density, high), and navigational challenge (no wayfinding, wayfinding). Navigational errors were analyzed as a function of visibility, traffic density, and type of turn cue (landmark, sign). Partial Eta squared statistics (η²) are reported as indices of effect size and Tukey’s HSD tests of means are used for post-hoc analyses.

The second stage involved calculating an index of speed adjustment for each participant and condition, and then using this index to create composite measures of driving performance that factored in speed compensations. These composite data were then analyzed using repeated measures factorial analyses of variance to assess the impact of the visibility, traffic density, and navigational challenge variables on composite measures of collisions, hazard RT, SD of lane position, and navigational errors.

The final stage was exploratory insofar as this study was primarily designed to measure average differences in the effects of challenge variables rather than assess the impact of individual differences. Nonetheless, given that a number of individual difference measures had to be collected to describe the sample, these measures were used to determine whether older drivers adjusted their speed commensurate with deficits in their sensory or attentional capacities as might be predicted by Baltes’ (1997) notion of loss-based compensation in older adults. Full-scale multivariate analyses were inappropriate given the limited sample but preliminary correlations were carried out to see if trends were in the predicted directions.

3.1. Raw data

First, in order to measure compensatory behavior, analyses were performed to assess the effects of the manipulations on driving speed. Each of the challenge factors resulted in a significant speed adjustment, as shown in Fig. 1. Driving speed was significantly lower in fog than in good visibility (M difference = 5.3 kph; F(1,18) = 11.7, p = .003, η² = .39) and in high-density traffic than low (M difference = 1.2 kph; F(1,18) = 22.65, p < .001, η² = .56). Furthermore, driving speeds were 5.8 kph lower on average when drivers were wayfinding while driving than when they were just following the road (F(1,18) = 42.89, p < .001, η² = .70). The older drivers reduced their speed in the face of each driving challenge but
there were no significant interactions between factors in this sample (the closest contender was the density × wayfinding × visibility interaction at \( F(1,18) = 2.89, p = .11 \)). This is surprising given that slowing for one challenge should help drivers deal with any other challenges presented in combination. This means that effects should be sub-additive, producing notable interactions between factors.

Driving performance was assessed in terms of hazard response, steering, and wayfinding errors. Collisions were rare and there were no significant effects (\( p > .1 \) for all), but as can be seen from Fig. 2a, most collisions occurred in high-density traffic. Traffic density had a significant effect on hazard RT (\( F(1,18) = 4.45, p = .049, \eta^2 = .20 \)) but this effect was subsumed by a three-way interaction between visibility, traffic density, and navigational challenge (\( F(1,18) = 9.06, p = .008, \eta^2 = .34 \)). The shape of the interaction was not as anticipated, though, as shown in Fig. 2b. Latencies were lowest under the good visibility – low density – no wayfinding challenge condition as predicted (Tukey’s HSD \( p < .05 \) only for the other low-density conditions and the good visibility – high density – no wayfinding condition though). However, the highest latencies were not in the conditions that combined visibility, traffic density, and wayfinding challenge, and in fact, there were reversals in the effects of the visibility and traffic density manipulations depending on the navigational condition. High traffic density and poor visibility each increased hazard RT by a significant amount when there was no wayfinding challenge (Tukey’s LSD \( p < .05 \) for both), though they each reduced it slightly when there was a wayfinding challenge (Tukey’s LSD \( p > .05 \)).

Standard deviation of lane position was reasonably stable in the face of different driving challenges (see Fig. 3). The only factor that had a significant effect was the navigational manipulation (\( F(1,18) = 11.29, p = .003, \eta^2 = .38 \)), with participants having larger lane deviations when they were driving while looking for signs and landmarks to direct them to their destination (\( M \) difference = .012 m).

In the wayfinding condition, each driver had to make two turns, one in response to a sign and the other in response to a landmark. The percentages of missed turns are presented in Fig. 4. There were marginally more missed turns in good visibility conditions than poor (\( F(1,18) = 3.83, p = .07, \eta^2 = .18 \)). There was also a trend to more missed landmarks than signs, which would not be surprising given that for landmarks participants had to remember not only the appearance of the landmark but the direction to turn. This effect was not significant though (\( F(1,18) = 2.58, p = .13, \eta^2 = .13 \)). There were few errors of commission (extra turns) and no significant effects (\( F < 1 \)), but all of the excess turns were made in good visibility conditions. When the average percentage of extra turns was measured (calculated as the percentage of the six distractor
turns made in each drive), the percentages were 1.75% in the low density – good visibility condition and 0.88% in the high density – good visibility condition.

To summarize, each manipulation had an effect on driving speed. There was evidence of compensatory slowing for fog, high-density traffic, and navigational challenge, though the effects appeared to be independent insofar as there were no interactions between factors. There was a three-way interaction in the hazard RT data. The results were not as predicted though. In fact, analysis of variance revealed the main effects were in the opposite direction of what would be expected, with higher hazard RT in good visibility than poor (M difference = 4 ms, p < .05), low-density traffic than high (M difference = 24 ms, p < .05), and in the no wayfinding than wayfinding condition (M difference = 4 ms, p < .05). Given this pattern of results, it seems plausible that the older drivers managed to nullify or partly reverse the deleterious effects of fog, high-density traffic and navigational challenge on hazard RT by reducing their driving speed in these conditions.

3.2. Composite variable analysis

Given notable differences in driving speed across conditions, it is inappropriate to interpret raw driving performance measures in isolation. For example, the difference between hazard RT for the easiest and most demanding conditions (the good visibility – low density – no wayfinding and the poor visibility – high density – wayfinding conditions) was not statistically significant – but the driving speeds were 13 kph slower in the most difficult condition than the easiest condition (a 15% reduction in speed, p < .001). If speed is truly used to compensate for the difficulty of the drive, then drivers are achieving improved driving performance at the cost of reduced driving speed. This complicates interpretation of the driving performance data and as a result, composite measures were derived to factor in the effects of speed compensation for each of the challenge variables.

To our knowledge, this is the first time there has been an attempt to look at the effects of a variety of different challenge variables at the same time in older drivers. As a result the following strategy was used to factor in speed adjustment, given that different drivers might compensate in different ways to different conditions and combinations of conditions. First, for each participant an adjustment index was calculated for each combination of conditions, using the driving speed in the baseline condition (good visibility – low density – no wayfinding) in the numerator, and the driving speed for the condition in question in the denominator. This adjustment factor basically measured increases or decreases in speed as compared to the baseline condition. Thus, the baseline condition was assigned an adjustment factor of 1.00. Lower speeds in the challenge than baseline condition would produce an adjustment factor greater than 1.00. Higher speeds in the challenge than baseline condition would result in an adjustment factor less than 1.00.

Formulas, means, and standard deviations for each of these adjustment factors are listed in Table 1. Preliminary analyses were carried out to determine the relationships between the various speed adjustment indices. First, correlations were calculated among the three first order challenges (visibility alone, traffic density alone, and navigational challenge alone). Of the individual speed adjustments for poor visibility, high density, and navigational challenge, the only significant correlation was between the adjustments for poor visibility and navigational challenge (r (17) = .60, p = .006). This correlation indicates that those that reduced their speed more for fog also reduced their speed more for navigational challenge. The speed adjustment index for the traffic density challenge did not correlate significantly with the speed adjustment indices for visibility or that for navigational challenge.

To summarize, each manipulation had an effect on driving speed. There was evidence of compensatory slowing for fog, high-density traffic, and navigational challenge, though the effects appeared to be independent insofar as there were no interactions between factors. There was a three-way interaction in the hazard RT data. The results were not as predicted though. In fact, analysis of variance revealed the main effects were in the opposite direction of what would be expected, with higher hazard RT in good visibility than poor (M difference = 4 ms, p < .05), low-density traffic than high (M difference = 24 ms, p < .05), and in the no wayfinding than wayfinding condition (M difference = 4 ms, p < .05). Given this pattern of results, it seems plausible that the older drivers managed to nullify or partly reverse the deleterious effects of fog, high-density traffic and navigational challenge on hazard RT by reducing their driving speed in these conditions.

### Table 1

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<thead>
<tr>
<th>Type of speed adjustment</th>
<th>Mean</th>
<th>SD</th>
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<tr>
<td>Visibility only</td>
<td>1.078</td>
<td>.11</td>
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<td>Density only</td>
<td>1.004</td>
<td>.05</td>
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<tr>
<td>Wayfinding only</td>
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<td>.06</td>
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<td>Density and visibility</td>
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<td>.13</td>
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<td>Density and wayfinding</td>
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<td>.07</td>
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<td>Visibility and wayfinding</td>
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<td>.19</td>
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<tr>
<td>Density and wayfinding</td>
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<td>.20</td>
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<td>Baseline (GV LD no wayfinding)</td>
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The analyses of variance were then conducted again, using the composite measures of driving performance. Composite hazard RT are shown in Fig. 5a. When these data were analyzed there were main effects of visibility (F (1,18) = 12.42, p = .002, η² = .408) and navigational challenge (F (1,18) = 37.04, p < .001, η² = .673), with mean transformed hazard RT 127 ms higher in fog than in good visibility and 132 ms higher in the wayfinding than in the non-wayfinding conditions. There was no longer a main effect of density though (F < 1, with transformed RT only 2 ms more in high-density traffic than low). This might be expected if the effects of density were over-estimated compared to the other two challenge variables in the raw performance data, because there was only a minimal reduction in speed as a result of increased traffic density (1.2 kph on average) and larger speed compensations for the other two challenges (each in excess of 5 kph). Therefore, drivers maintained moderately high speeds in high-density traffic, but it came at the cost of increased hazard RT, whereas they reduced
trend for fog to decrease the impact of the other manipulations in the composite hazard RT data.

There were no significant effects in the composite collision data (The closest contender was a visibility × navigational challenge interaction: $F(1,18) = 2.08$, $p = .17$.) See Fig. 5b. However, analyses of composite SD of lane position data revealed some effects (Fig. 6). There was a main effect of navigational challenge ($F(1,18) = 47.40$, $p < .001$, $\eta^2 = .725$), a main effect of visibility ($F(1,18) = 7.78$, $p = .012$, $\eta^2 = .30$), and a marginal density × visibility × navigational challenge interaction ($F(1,18) = 3.40$, $p = .082$, $\eta^2 = .159$). This interaction also took a synergistic form insofar as the interactive effect of the three variables ($0.0597$ m) was marginally greater than the sum of the independent effects of the three variables (summed effect = $0.0540$ m: $t(18) = 1.85$, $p = .082$). As before, comparisons were made to determine how visibility conditions affected the influence of other manipulations. In this case, visibility conditions had little effect on the magnitude of the differences in lane position as a function of the other manipulations. Tukey’s HSD tests of means revealed that when there was no wayfinding the difference between high and low-demand conditions was $0.005$ m in both fog and good visibility ($p < .05$ for both). Similarly, the differences between wayfinding and no wayfinding conditions were $0.030$ and $0.033$ m in fog and good visibility respectively ($p < .05$, low-density condition for both). In contrast to the hazard RT data, for SD of lane position, the combined effects of the variables were stronger in fog than in good visibility though ($p < .05$ for the discrepancy in the size of the differences). In particular, the difference between the low density – no wayfinding and high density – wayfinding conditions $0.045$ m in fog ($p < .05$) as compared to $0.026$ m in good visibility ($p < .05$).

Composite scores for the missed turns were calculated using the good visibility – low density – wayfinding condition speeds as baseline. Interestingly, when the percentages of missed turns were transformed to take into account speed accommodations, there were no significant effects (visibility: $F(1,18) = 2.49$, $p = .13$; density: $F(1,18) = 2.43$, $p = .14$; turn type: $F(1,18) = 2.43$, $p = .14$). This suggests that the main effect of visibility seen in the raw performance data may be accounted for by the faster driving speeds adopted in good visibility conditions (speed caused more missed signs and landmarks).

3.3. Exploratory analyses

Sensory and attentional measures as they predict driving performance and indices of speed adjustment (Baltes’ [1997] Selection, Optimization, Compensation theory suggests that older adults adjust their behavior commensurate to their individual deficits and strengths. As a result, analyses were carried out to find out if scores
on the psychological tests predicted the amount of speed adjustment for each challenge. Before looking at the correlations between psychological tests and measures of driving performance and speed compensation, it is informative to consider the correlations among the different tests. Table 2 presents the inter-correlations between the various psychological tests. In this sample, the only significant correlation was that between the Divided and Selective Attention subscales of the UFOV ($r(17) = +.47$, $p = .044$), though there was a marginal correlation between the ETDRS test of acuity the Pelli–Robson Contrast Sensitivity test ($r(17) = -.43$, $p = .07$). Age did not prove to be a significant predictor of any of the test scores. Table 2 also documents the relationships among individual difference variables and indices of overall driving performance. The most notable correlations were those between age and driving speed ($r(17) = +.55$, $p = .02$) and those between the Perceptual Speed subscale of the UFOV and collisions, hazard response time, and the number of missed turns ($r(17) = +.84$, +.57, and +.57 respectively, $p < .05$ for all). Thus, in this sample, the UFOV Perceptual Speed scale was the best predictor of driving performance.

However, a more complex pattern of results emerged when the psychological test scores were correlated with indices of speed compensation, as shown in Table 3. Neither of the sensory measures predicted driving performance but the ETDRS test of acuity correlated with the speed adjustment to traffic density ($r(17) = +.56$, $p = .012$). Individuals with poor visual acuity reduced their speed more in high-density traffic. Contrary to prediction, the Pelli–Robson contrast sensitivity test did not correlate with speed adjustments to fog though ($r(17) = -1.7$, $p > 1$). However, the average contrast sensitivity scores in this sample were worse than is typical, and as a result, it may be important to test this idea again with a larger and more diverse sample.

Similarly, although the Selective and Divided Attention subscales of the UFOV did not predict overall driving performance, they did predict speed adjustments. The Selective Attention subscale from the UFOV correlated significantly with speed adjustment indices for traffic density and navigational challenge ($r(17) = +.54$ and +.48 respectively, $p < .05$ for both), as might be expected given that traffic density produces visual clutter, and given that finding signs and landmarks requires selective attention. The Divided Attention subscale of the UFOV correlated significantly with speed adjustments for the combination of poor visibility, high density, and wayfinding challenge ($r(17) = +.59$, $p = .008$) and the adjustments for visibility alone, density alone, and visibility and wayfinding in combination ($r(17) = +.46$, +.49, and +.62 respectively, $p < .05$ for all). However, contrary to prediction, the correlation between Divided Attention scores and speed adjustments for the navigational chal-
lenge alone was not significant, though it was in the right direction \( r(17) = +0.38, p = .10 \). It is only when the wayfinding challenge was combined with others that the effects became statistically significant. This may be because there was less variability in the speed adjustment index for wayfinding alone than for wayfinding in combination with other challenges (see SD in Table 1). Overall, given that high scores on the UFOV indicate reduced performance (slower responses), these positive correlations mean that those with poorer UFOV performance reduced their speed more in face of driving challenges.

4. Discussion

This study makes a number of contributions. It was the first to use a driving simulator to measure the interactive effects of visibility, traffic density, and navigational challenge on older drivers. Information about how healthy older drivers cope with various challenges alone and in combination is useful when trying to assess the impact of disorders such as Alzheimer’s and Parkinson’s disease. This study has practical implications for those evaluating in-vehicle navigation devices insofar as it is important to understand how drivers perform without benefit of these technologies when determining whether the devices put drivers at risk. The wayfinding manipulation in this study was novel insofar as it had participants finding their way to a specified town using memorized directions, and thus it did not require recourse to maps or human co-pilots (When wayfinding requires maps or other people it is possible that the physical demands of holding the map or turning to speak to another individual may interfere). The results indicate that even following memorized directions produces interference. It was not the unfamiliar driving environment per se that produced the problems because drivers in both wayfinding and non-wayfinding conditions were driving down unfamiliar roads (each road was unique and novel to the participant). It was the need to hold directions in memory and then use them at the appropriate time that produced interference. This interference was evident in hazard RT and steering. Even with only two turns per drive, there were a considerable number of missed turns though the missed turns were especially likely to occur in good visibility conditions (where drivers adopted higher driving speeds).

Overall, the results indicate that reduced visibility, increased traffic density, and navigational challenge affect driving speed and driving performance. By looking at how much drivers adjusted their speed to the different challenges alone and in combination, it is possible to obtain information about how these challenges were perceived. The older drivers reduced their driving speed in fog, high-density traffic, and while wayfinding, which suggests that each condition was regarded as a threat, though there were no interactions between factors. The magnitudes of these speed adjustments were enough to nullify or partly reverse the effects of the challenge manipulations in the hazard RT data, making the response times in fog, high-density traffic, and wayfinding conditions comparable to those in good visibility, low-density traffic, and no wayfinding conditions. When an index of speed compensation was calculated for each condition and driver, these measures correlated with measures of visual acuity and the Selective and Divided attention subscales of the UFOV. In particular, individuals with diminished capacities reduced their speeds more in response to visibility, traffic density and wayfinding challenge than those who scored better on these tests. This suggests that the older drivers were adjusting their speed to match driving conditions and their own individual capacities, as predicted by Selection, Optimization, and Compensation theory (Baltes, 1997).

Given that there were marked differences in driving speed between conditions, raw measures of driving performance were difficult to interpret. As a result, composite measures were created that calculated for driving performance in each of the challenge conditions, factoring in the amount of speed compensation for each individual. Analyses of variance on composite hazard RT and SD of lane position data revealed three-way interactions (visibility × traffic density × navigational challenge). These interactions were synergistic in form, insofar as the interactive effects were greater than the sum of main effects.

The presence of these interactions might be taken as partial support for Baldwin’s (2002) sensory–cognitive interaction theory, which suggests that low-level sensory factors tap some of the same resources as higher-level cognitive tasks that demand attention or executive working memory. The interactions did not take the expected form though. For hazard RT, the effects of the traffic density and navigational challenge manipulations were significantly stronger in good visibility conditions than poor. In contrast, for SD of lane position, combined density and navigational challenge manipulations had greater effects in fog than good visibility (the opposite pattern to that observed in hazard RT).

The different patterns of interaction between fog and the other challenge variables in hazard RT and steering variability can best be understood in terms of the requirements of each performance variable. Driving as a whole requires a number of different attentional operations, including orienting, visual search, filtering/focusing, multiple-object tracking, and multiple action monitoring (Trick et al., 2004) and different measures of driving performance stress some operations more than others. Hazard detection requires visual orienting but in this study, given the number of hazards per drive, participants may have also adopted the strategy of searching for hazards. Clutter would make visual search more difficult. The reduced impact of high-density traffic in fog might make sense if the fog served to make the traffic (visual clutter) less visible thus reducing the load on selective attention. Similarly, it is possible that the wayfinding manipulation was more difficult in good visibility conditions than poor because the fog served to obscure some of the clutter in the image (the other signs). Thus, fog may serve to reduce the load on selective attention as it is used in search tasks and this would explain why the deleterious effects of high-density traffic and wayfinding were worse in good visibility conditions than poor for the hazard RT data (Strangely, the combined effects of the two variables were about the same in good and poor visibility conditions though).

In contrast, steering is thought to require ambient vision (Wickens, 2002) but it does not require visual search insofar as there is no need to select visual targets among distractors. Fog may facilitate selective attention because it obscures visual clutter but that does not reduce steering variability in the face of either density or wayfinding challenge. In fact, steering was significantly worse in fog than in good visibility when high-density traffic and wayfinding challenge occurred in the same drive. The differing patterns of results observed for hazard RT and SD of lane position are consistent with other studies that show discrepancies in the impact of independent variables on hazard response and steering (e.g., Reed Jones et al., 2008; see also Wickens, 2002).

5. Conclusions

This study has several implications. First, it provides support for the idea that there are interactions between factors that are more sensory in nature (such as the low contrast image conditions produced by fog) and those that involve higher order factors such as selective attention (necessary to deal with clutter produced by traffic) and executive working memory (necessary for carry-
ing directions in memory and using them at the appropriate time). Nonetheless, the results reveal complexities that call into question the simple sub-division of resources as suggested by resource theories. This is because different components of driving performance are affected in different and sometimes opposite ways by different combinations of challenge. This result may reflect the fact that different measures of driving performance require different attentional operations (Trick et al., 2004), and thus, the effects of challenge variables change with the dependent measure in question.

This study also has ramifications for Baltes’ (1997) Selection, Optimization, and Compensation theory. There are many ways that older drivers may compensate for age-related deficits, including avoiding certain situations (unfamiliar roads, left-hand turns across traffic, driving at night), performing extra eye or head movements, bringing along a co-pilot to help with the drive, but one simple way to compensate is by slowing down. The older adults in this sample reduced their driving speed substantially to compensate for poor visual acuity and driving in unfamiliar urban environments. As a result, hazard RT was significantly higher in high-density traffic conditions and two speeds tested with a driving simulator. Accident Analysis and Prevention 31, 545–553.

This highlights the importance of looking at compensation as well as performance when evaluating older drivers at risk (see Brouwer et al., 1988). However, at this point, further research is required with larger and more diverse samples of older drivers before firm conclusions can be made.

Acknowledgements

The Ontario Neurotrauma Foundation, Canadian Foundation for Innovation, Ontario Innovation Trust, and Auto21: Network Centres of Excellence funded this research. Lauren Meegan helped with testing participants and Robert Ramkhalawansingh looked over an earlier draft of this article. Some of the data from this study were presented at the 5th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, Big Sky, Montana, June 22–25, 2009. We would also like to thank an anonymous reviewer who suggested that we include the individual differences analyses.

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