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Exploring the relationship between perceptual-cognitive function and driver safety: *prediction and transfer*

par

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Résumé

La conduite automobile continue d'être le mode de transport dominant dans le monde et le nombre de véhicules sur la route ne devrait qu'augmenter au cours des prochaines décennies. Dans un même temps, l'évolution démographique qui se produit actuellement dans le monde industrialisé implique que la proportion de conducteurs âgés sur la route devrait augmenter considérablement. L'âge s'accompagne de changements de grande envergure dans les systèmes physiques, sensoriels et cognitifs, entraînant des changements fonctionnels qui peuvent être subtils ou profonds. Nous commençons seulement à comprendre comment la variabilité normale et pathologique de ces mesures fonctionnelles affecte les performances de conduite et la sécurité.

Le développement d'un outil fiable et fondé sur des données probantes pour distinguer les conducteurs prudents des conducteurs dangereux continue d'être une préoccupation majeure pour les chercheurs en gérontologie, en accidentologie et en clinique. L'accumulation de preuves suggère maintenant qu'il existe un lien important entre des capacités cognitives spécifiques telles que la vitesse de traitement de l'information et l'attention, et les performances de conduite. Continuer à explorer cette relation pour peut-être un jour développer un tel outil est une entreprise importante. Une autre implication de la relation entre les capacités cognitives et les performances de conduite est que les interventions conçues pour les améliorer ou les maintenir pourraient éventuellement améliorer ou maintenir la sécurité et le confort de conduite des individus à court et à long terme.

L'objectif de cette thèse est triple. Premièrement, il développe et valide une nouvelle méthodologie pour évaluer les performances de conduite des jeunes adultes et des adultes plus âgés à l'aide de scénarios de simulation de conduite personnalisés. Deuxièmement, elle pousse l'état de nos connaissances sur la façon dont les capacités cognitives sont liées à la performance de conduite en démontrant que la performance sur un test intégratif d'attention dynamique et de vitesse de traitement - c'est-à-dire le suivi d'objets multiples en 3D (3D-MOT) - prédit les performances des conducteurs de différents groupes d'âge. Enfin, elle offre des preuves suggérant que la formation 3D-MOT améliore réellement la fonction attentionnelle et la vitesse de traitement en transférant la performance sur un test indépendant de ces capacités et, finalement, que cette amélioration pourrait se traduire par une amélioration des performances de conduite.

Mots-clés : Sécurité au volant, vieillissement, entraînement cognitif, simulateur de conduite, attention, vitesse de traitement de l'information, apprentissage, transfert

Abstract

Driving continues to be the world's dominant form of transportation and the number of vehicles on the road is only projected to increase in the coming decades. At the same time, the demographic shift currently occurring in the industrialized world implies that the proportion of older adult drivers on the road is set to increase substantially. With age comes wide-ranging changes in physical, sensory and cognitive systems resulting in functional changes that can be subtle or profound. We are only beginning to understand how both normal and pathological variability in these functional measures affect driving performance and safety.

Developing a reliable, evidence-based tool to distinguish safe from unsafe drivers continues to be a major preoccupation for gerontology, accidentology, and clinical researchers alike. Accumulating evidence now suggests that there is an important link between specific cognitive abilities such as speed-of-processing, attention, and driving performance. Continuing to explore this relationship in order to perhaps one day develop such a tool is an important endeavour. Another implication of the relationship between cognitive abilities and driving performance is that interventions designed to improve or sustain these might conceivably enhance or maintain individuals' driving safety and comfort in the short- and long-term.

The purpose of this thesis is threefold. First, it develops and validates a novel methodology for assessing both young adult and older adult driving performance using custom driving simulator scenarios. Second, it pushes the state of our knowledge of how cognitive abilities relate to driving performance by demonstrating that performance on an integrative test of dynamic attention and speed-of-processing—i.e., 3-dimensional multiple object tracking (3D-MOT)— predicts how drivers of different age groups perform. Finally, it offers evidence to suggest that training 3D-MOT actually enhances attentional function and speed-of-processing by transferring to performance on an unrelated test of these abilities and, ultimately, that this improvement might translate to improved driving performance.

Keywords: Driving safety, ageing, cognitive training, driving simulator, attention, speed-of-processing, learning, transfer

Table of contents

List of tables

List of figures

List of acronyms and abbreviations

3D-MOT: 3-dimensional multiple object tracking

ACTIVE: Advanced Cognitive Training for Independent and Vital Elderly

AD: Alzheimer’s disease

AN(C)OVA: Analysis of (co)variance

CERES : Comité d’éthique de la recherché en santé

CONSORT: Consolidated Standards of Reporting Trials

CTT: Color Trail Test

ETDRS: Early Treatment Diabetic Retinopathy Study

EF: Executive functions

IHAMS: Iowa Healthy and Active Minds Study

MOMMSE: Mattis Organic Mental Syndrome Examination

MMSE: Mini-Mental State Examination

MS: Multiple sclerosis

qEEG: Quantitative electroencephalography

RMS: Root mean square

RT: Reaction time

SAAQ: Société de l’Assurance Automobile du Québec

SDLP: Standard deviation of lateral position

Stroop: Stroop Color and Word Test

SDMT: Symbol Digit Modalities Test

Timed IADL: Timed instrumental activities of daily living

TMT-A: Trail Making Test part A

TMT-B: Trail Making Test part B

UFOV: Useful Field of View

VA: Visual acuity

VF: Visual field

WCST: Wisconsin Card Sorting Test

WM: Working memory

“The beautiful thing about learning is that nobody can take it away from you.”

– B.B. King

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Introduction

1.1 Driving

1.1.1 A dominant yet risky mode of transportation

It has been estimated that by the year 2030 upwards of 2 billion cars will be on the road, representing the most dominant form of transportation in much of the world (1). Indeed, as of 2020, roughly 27 million individuals possessed a license to drive in Canada alone (2). Great strides have been taken to try and improve road safety: from advances in modern vehicle and road design, to major public education initiatives such as the Canadian Year of Road Safety 2011. The effect of such efforts should not be understated: in Canada, the fatality rate per 10,000 motor vehicles registered has dropped from 1.52 in 2001 to 0.68 in 2020 (2). While such statistics also include pedestrian victims of driving accidents, over half of these fatalities were among drivers of motor vehicles such as cars, trucks and motorcycles. Furthermore, a 2004 report by the World Health Organization suggested that, each year, roughly 1.2 million people worldwide are killed in road crashes and another 20-50 million are injured (3). They forecast that this death toll could increase by up to 50% in the next 20 years and become the sixth major cause of deaths worldwide if action is not taken. To this end, a 2020 resolution by the United Nations General Assembly proclaimed 2021 the beginning of the Second Decade of Action for Road Safety (4). In this resolution, they called upon Member States to continue making major commitments to improve road safety and to consider adopting comprehensive, science-based legislation on key risk factors.

1.1.1.1 Factors contributing to driving accidents

A number of risk factors have been highlighted in the accidentology literature as contributing to crashes and fatalities while driving. Perhaps the most significant among these is youth, inexperience, and the personality traits as well as social contexts these engender (5,6). Younger drivers, especially males, are well-known for driving more recklessly and at unsafe speeds, and this is even more true in the presence of their peers (7). Younger drivers are also more likely to take risks by driving while fatigued or distracted where older drivers are more likely to self-limit in such situations (8). While these individuals may not necessarily drive under the influence of alcohol or drugs more regularly than more experienced drivers, research has suggested that they are the most likely to sustain severe injury in situations when such impairments were reported as causative factors, likely due to more inconsistent seatbelt usage (5,8,9). Inexperienced drivers also appear to be overconfident in their abilities: they both fail to perceive hazardous situations being as dangerous as older drivers do and, additionally, perceive themselves as more skilled than older, more experienced drivers (10). In stark contrast with inexperienced drivers' subjective evaluations of their driving ability, research has shown that novice drivers are less effective at distributing their visual attention while driving and often exhibit less effective visual search and acquisition strategies (11,12). Estimates place young drivers at a 5 to 10x greater likelihood of being involved in and sustaining injuries during road crashes compared to the safest driving groups (13–15).

Older adult driver risk factors during driving are very different by comparison. Whereas alcohol and drug use is the leading cause of fatal accidents for drivers under 60 years (5), older driver frailty is the primary cause of elevated fatalities in drivers over the age of 70. In fact, these drivers are generally among the least likely to be involved in accidents when you account for biases introduced by the relatively low mileage of accident-prone older adults (15,16). This may be explained, in part, by the fact that older drivers are often known to strategically avoid traveling at night, on roads with higher speed limits, on more complex urban roads, and on unfamiliar roadways (17).

Not all ageing is equal, however. The older adult population is characterized by great heterogeneity and many older individuals eventually experience steady declines in physical, sensory, and cognitive functions that are ultimately detrimental to driving performance (18). When they do get into accidents, these are disproportionately associated with being in intersections and other complex traffic situations, turning errors, and failure to yield (5,19–21). Research on elderly drivers with mild cognitive impairment or dementia has sometimes found that these individuals are involved in more crashes relative to their cognitively normal peers and are more often judged to be at-fault (22,23). Furthermore, the fact that older adults often feel the need to self-regulate their own driving suggests that many may be compensating for a decreased sense of comfort and ease of driving in more challenging or unfamiliar circumstances (24,25). This possibility is one that is not lost on driving safety researchers, and considerable effort has been made to understand what age and health-related changes may predict increased driving risk, self-regulation, and driving avoidance.

1.1.2 How ageing changes driving behaviour

A consequence of the ongoing demographic shift in industrialized countries is that the elderly now represent the fastest growing segment of the driving population (26). According to Statistics Canada, driving remains the most popular form of transport for older adults in Canada (27). Additionally, individuals are increasingly choosing to drive well into their eighties and nineties as medical advances continue to increase human life and healthspan (28). At the same time, ageing is associated with a wide range of changes in physical, perceptual, and cognitive functions considered critical for safe engagement in a task as complex as driving (29). There is, thus, a clear impetus for further study into how driving behaviour changes with age as well as the causes of such change.

Molnar et al. offer an excellent, in-depth discussion of the complex and multifaceted causes of self-regulation and driving avoidance in older adults (17). First, they draw a distinction between driving self-regulation and avoidance where the former is typically defined in relation to some declining ability and the latter to more external factors. Indeed, research by Moták et al. suggests that even younger drivers engage in driving avoidance under many circumstances (e.g. driving at night or in bad weather), albeit less than older adults (30). This same study also demonstrated correlations between increased driving self-regulation and negative health-related perceptions as well as integrative measures of cognitive ability such as the Digit Symbol Substitution Test in older adults.

While lifestyle and preference changes dissociated from age-related declines are cited as important factors in driving avoidance (e.g., reduced need to travel and increased availability of transportation alternatives, etc.), increased awareness of specific functional impairments such as changes in visual, motor, and cognitive ability are frequently reported in cases of self-regulation. Though a detailed discussion of the relationship between different visual sensory measures and driving performance is beyond the scope of this work (see (31) for a detailed review), changing visual function is among the most commonly cited reasons for driver self-regulation (32). Additionally, older individuals often report a more generalized feeling of discomfort or increased fear of getting into a crash while driving as a factor contributing to self-regulatory behaviour (25). Some researchers have suggested that this insecurity may be related to an automatic self-regulation process for individuals lacking awareness of an underlying functional loss (33). Perhaps related to this, older adults reporting more negative self-perception of their driving ability were also found to engage in more self-regulatory practices and reported driving fewer kilometers per year compared to more confident peers (34,35).

Older drivers may also self-regulate their actual driving performance: Trick et al. found that when altering mental load through experimental manipulation of visibility conditions, traffic density, and wayfinding challenge, older drivers were significantly more likely to reduce their driving speed to compensate for increased challenge (36). This effect was especially pronounced in drivers with worse scores on tests of sensory or attentional function. Similarly, Cuenen et al. found that older drivers with impairments in attention capacity were more susceptible to distraction: they exhibited worse lane keeping performance and higher simulated crash occurrence in situations with a high demand on vehicle handling and information processing compared to individuals with better attentional ability (37). Collectively, these compensatory strategies have been referred to as “tactical self-regulatory practices” (17). Also included among these are behaviours such as: a greater propensity to avoid potentially distracting secondary activities like listening to the radio, talking on a cell phone while driving, and alterations in driving maneuvers such as overtaking and gap acceptance in traffic.

The most extreme form of driver self-regulation is known as driving cessation i.e., a complete discontinuation of driving. It generally occurs as a result of a recent health decline or accident and is often involuntary. Although to many this may seem like an innocuous enough precautionary measure, driving cessation and the associated loss in ease and freedom of mobility is linked to the development of a number of negative health, emotional, and societal outcomes. These include increased placement in long-term-care, depressive disorders, social isolation, further health decline, and even increased mortality (38,39). It is believed that the relationship between driving cessation and these negative outcomes is mutually causative. In other words, they aren't simply related to the original health changes precipitating driving cessation. Instead, simply giving up driving may precipitate further decline.

This fact has motivated researchers to try and better understand what specific functional deficits are actually most predictive of increased driving risk. It is hoped that it may one day be possible to intervene and rehabilitate individuals with those impairments to keep them driving safely for longer and to help maintain their autonomy. Alternatively, such knowledge could be used by medical professionals to better inform individuals if objective criteria suggest that they might be putting themselves and others at risk. There is, additionally, the basic moral imperative to apply evidence-based standards to cases where involuntary revocation of someone's license may be in the public's best interest. This is not a hypothetical issue: in Canada, most provinces require adults 75 and older to disclose the state of their health and adults over the age of 80 must get tested every two years to gauge their continued fitness-to-drive (40).

One must also consider that many careers involve driving a motor vehicle, often with passengers. Thus, there is a clear need for objective and non-discriminatory criteria that can identify when an individual is no longer competent enough to carry out their work duties. This final point has real-world precedent: in 1988, the Florida Education Association fought a successful legal battle against the Florida Department of Education when the latter tried to institute a mandatory retirement age for school bus drivers due to concerns that family physicians were being too lenient while screening them for safety (41). The court ultimately ruled that this mandatory retirement constituted age discrimination as it was not a Bona Fide Occupational Qualification for driving safely.

With these considerations in mind, a number of visual-sensory and cognitive functional measures have been evaluated for their utility at identifying drivers potentially at-risk of getting into accidents and for their relationship with driving performance.

1.1.3 Predicting driving safety and performance

1.1.3.1 Visual function

Driving is undoubtedly a visually-demanding task. As such, it is unsurprising that governments and licensing authorities the world over dictate that individuals must exhibit a certain level of visual function to be granted and maintain the privilege. While the exact visual requirements vary greatly between polities, they almost always involve a certain level of best-corrected static visual acuity (VA) in the better eye—most often 20/40 on a Snellen chart. Many also require a reasonably intact visual field (VF) consisting of a continuous 110°-140° horizontally at minimum, though this is not as universal as visual acuity requirements. These two functional measures represent the full extent of visual requirements for licensure in a majority of countries (42). This is true both for older adults who may be experiencing age-related decline in visual ability as well as for younger adults with visual impairments caused by other factors.

Surprisingly, despite its ubiquity as a legal requirement and what seems to be broad public support for VA screening to drive, there is a lack of a strong relationship between VA and elevated real-world accident risk (31,43). While VA and other visual functions have been linked to driving *performance* (i.e., to objective or subjective measures of driving skill other than accident involvement) in experimental contexts (44–46), only weak correlations or mildly increased odds ratios between these measures and real-world collisions have ever been shown (31,47–49). As discussed by Owsley & McGwin, this may be because VA tends to subserve driving skills related to navigation (e.g., reading road signs) rather than the visual skills necessary for safe operation of a motor vehicle. Additionally, static VA is generally measured under conditions of high contrast and luminance with no secondary tasks or distractions i.e., conditions that simply do not reflect the great visual complexity and varying contexts of driving. To this point, more comprehensive spatial vision tests investigating contrast sensitivity have sometimes been shown to be a more reliable indicator of crash risk compared to VA (50,51).

Alternatively, it is also possible that a would-be association between collisions and visual impairment is masked by increased self-regulation amongst visually impaired drivers. This interpretation is supported, in part, by research from Freeman et al. showing that lower baseline visual acuity was associated with greater odds of cessation of driving in unfamiliar areas two years later (52). It has also been supported via studies on crash involvement that showed subjective reports of decreased driving frequency and more strict self-restriction of driving contexts were linked to fewer crashes in older adults with various functional impairments (53,54). Finally, studies investigating the effects of sudden, artificial visual impairments in otherwise normally-sighted drivers often show a resulting impairment of performance in complex driving tasks (55–57). This can be interpreted as additional evidence that visual impairment affects driving ability—especially in driving contexts that visually impaired drivers seem to intentionally avoid. It is unclear from these studies whether or not this effect may be eventually mitigated (in full or in part) with longer-term visual impairment, however.

This pattern of increased self-regulation and impaired driving performance in experimental contexts, but weak or non-significant links with real-world accident risk, is generally consistent when examining other visual sensory measures such as: contrast sensitivity, dynamic VA, and even mild VF loss (58–61). Still, other studies have found exactly the opposite: that a majority of older drivers did not change their driving behaviour or self-reported driving confidence after five years despite worsening visual acuity and contrast sensitivity (62) and that they did not feel that their vision put them at risk of crashes or a need to avoid risky driving situations (63).

Put simply, the evidence for visual sensory functional impairment being linked to accident involvement is mixed. Considering that this is possibly mediated by increased driver self-regulation among visually impaired older adults, rehabilitation aimed at improving driver safety and confidence could have merit in cases where visually impaired individuals still meet minimum legal requirements for licensure. Additionally, there may be merit in teaching functionally impaired individuals about what forms of self-regulation are most likely to enhance their driving safety.

Some jurisdictions have taken these ideas even further by allowing more moderately visually impaired drivers (i.e., VA better than 20/200 but still below legal requirements), trained using assistive devices like bioptic telescopes in rehabilitation clinics, to continue driving if they can demonstrate their ability to do so safely and generally under specific conditions (64). This option is especially attractive to younger adults who may find complete driving cessation difficult to accept because of a more active lifestyle relative to older adults. Research has supported the notion that such educational interventions are effective at improving driver safety by promoting greater tactical self-regulation while driving (65). Research has shown, however, that the fact that older adults with significant age-related vision degradation often have comorbidities means that rehabilitation therapists and medical professionals simply do not consider offering them such opportunities in many cases (31).

Ultimately, while the preponderance of evidence points toward the importance of reasonable visual function to drive effectively, it seems that drivers are able to compensate for decreased visual quality at least to some extent. As previously discussed, this seems to occur primarily through increased self-regulation whereby drivers avoid road situations with decreased visibility and increased driving difficulty and unfamiliarity (53).

A crucial component that is missed in the link between basic visual sensory measures and driving, however, is the way drivers actually use and interpret the visual information available to them to guide their driving behaviour. Driving often takes place in highly dynamic, visually cluttered, and unfamiliar settings with shifting task demands. As a result, the current legal and practical standards for evaluating driver safety and fitness-to-drive are likely insufficient. When it comes to driving safety, it may be that the quality of visual input is secondary to higher level perceptual and cognitive processing of this information.

1.1.3.2 Perceptual and cognitive function - cognitive status

Researchers have also investigated perceptual and cognitive abilities as another set of functional measures with potential to predict driving performance and risk. It is important to distinguish between cognitive/mental status and perceptual-cognitive abilities at this stage: the former distinguishes cognitively normal individuals from those with dementia, cognitive impairment and certain other neurologic conditions while the latter refers to quantification of a broad range of constructs encompassing cognitive and perceptual domains like processing speed, executive function, memory, attention, visuospatial ability, and linguistic abilities, etc. It is also important to emphasize that the cognitive abilities in question are distinct from common-sensical notions about intellect or intelligence—though research has demonstrated that the psychometric concept of IQ is strongly correlated with many of these abilities (66).

Dementia is essentially *defined* by decline in perceptual and cognitive abilities, but it is also possible to measure broad variability in these abilities in neurologic and healthy populations as well. In fact, healthy ageing is associated with expected and natural declines in multiple domains of cognitive functioning (67). One can imagine how issues in planning and executing behaviour as well as attending to or efficiently processing visual information while driving might contribute to increased driving risk with or without a diagnosis of dementia.

Much like with practically every other age-related health condition, the prevalence of dementia in the population is projected to increase substantially in the next few decades as a result of the ongoing demographic shift (68). This fact has compelled considerable past and ongoing research into how it affects driving behaviour. One challenging aspect of studying the effects of cognitive status on driving safety has to do with the fact that dementia and cognitive impairment are umbrella terms for a constellation of deficits in perceptual and cognitive abilities. These can manifest in a variety of ways depending on the progression and type of underlying disease, which means that there can be great heterogeneity between individuals diagnosed with a neurodegenerative disease or cognitive impairment in terms of functional abilities.

This can make it difficult to dissociate what specific cognitive abilities may contribute to driver safety when studying this population using their diagnosis as a surrogate for functional loss. This is particularly true when the most widely used cognitive status screening tests aren't intended as thorough tests of cognition or of particular cognitive abilities and may also lack the sensitivity to detect mild cases of cognitive impairment. Nevertheless, the Alzheimer's Society estimates that one in three drivers with dementia continue to drive and are generally able to do so safely until their condition progresses (69).

As discussed in three separate reviews by Anstey et al., Molnar et al., and Man-Son-Hing et al., the literature on cognitive status and driving risk is somewhat mixed (17,70,71). Two large studies conducted in the United States of America investigated the link between performance on the Mini-Mental State Examination (MMSE) and either self-reported or state recorded crashes and did not shown a significant association (72,73). Importantly, neither of these studies specifically examined individuals diagnosed with dementia and their samples included large proportions of individuals that scored very well on the test. By comparison, Odenheimer et al. found that MMSE scores were strongly correlated with on-road driving performance assessed subjectively by three independent raters (including one professional driving instructor), though their sample was relatively limited (N = 30) and consisted of individuals with a broad range of cognitive skills, including a few that were referred from a dementia clinic (74). Additionally, Owsley et al. found that worse scores on the Mattis Organic Mental Syndrome Examination (MOMMSE)—a more comprehensive measure of mental status than the MMSE—were associated with a moderate increase in older adult crash risk (75).

Still, a 7-year retrospective study comparing 143 people diagnosed with Alzheimer's disease (AD) with 715 control subjects matched for age, sex, and country of residence also found no increase in crash or violation rates (76). They also found no correlations between neuropsychological test scores and either crashes or violations, though the authors acknowledge and did not account for the fact that the AD group likely drove fewer kilometers than their comparison group. On the other hand, a 5-year retrospective study by Cooper et al. studying state driving records of 165 individuals classified as having dementia showed a more than two-fold increase in crashes compared to an age- and sex-matched random sample of drivers (22). They also found that a large majority of drivers in the dementia group that got involved in a crash were judged at-fault and that over one third of them got into more than one accident.

Studies examining caregiver- and relative-reported crashes alongside state records suggest that individuals with AD and non-specific dementias may have as much as a 5 times greater crash involvement compared to controls (77,78). This could suggest that state records underestimate crash involvement, possibly because they do not capture a number of less serious accidents without significant enough property damage or injury to be reported. This interpretation is seemingly further supported by the results of a longitudinal study from Ott et al. that examined a combination of self-report, family-reported and state recorded accidents and driving violations and found that subjects with mild or very mild AD had experienced more accidents at baseline compared to age-matched controls (79). They also found that these subjects performed worse on a standardized road test evaluated by a professional driving instructor and that their driving performance declined more with time relative to the control subjects.

Interestingly, a recent retrospective cohort study that examined an impressive 29,730 individuals (~6% with dementia) followed for 7 years and found that the hazard ratio of crashes among older drivers with dementia was 0.56 compared to those without a diagnosis (80). The authors interpreted this reduced risk of crashes as potentially reflecting driver self-regulation—much like that found for cases of visual impairment—due to their lack of data on the driving exposure of their subjects. They point to other studies that also show a protective effect of dementia when not statistically accounting for the variability in driving frequency of their participants (81,82). Well-documented increase in self-regulation among drivers with dementia (83) is not the only parallel with visual impairment: despite the mixed results of research studying accident risk, results from studies examining driving performance measures in this population tend to paint a clearer picture.

Studies of simulator-based driving performance in older adults with dementia have found that they both drove and turned more slowly, applied less brake pressure when trying to stop, were more likely to accidentally drive off the road, and demonstrated greater inattention and slower responses leading to accidents at intersections (84,85). On-road studies using both qualitative and quantitative outcomes have demonstrated that older adults with dementia had greater difficulty with common maneuvers such as merging, signalling, left turns and lane changes (71,86,87). Lapses in attention and disinhibited behaviour common in Lewy body and frontotemporal dementias respectively have also been associated with more hazardous driving behaviour such as speeding, running stop signs, and collisions (88,89).

The existence of a few studies with contradictory results notwithstanding, the preponderance of evidence clearly demonstrates that cognitive status is associated with driving performance and real-world safety in cases of moderate to severe dementia. Indeed, this is even the consensus of an international panel of driving safety experts (90).

1.1.3.3 Perceptual and cognitive function – cognitive domains and perceptual abilities

More specialized tests of specific perceptual and cognitive factors have frequently proven to have greater sensitivity when it comes to predicting driver safety and performance than global tests of cognitive status. These tests are often less likely to suffer from ceiling effects common in quick screening tests like the MMSE (91). This may make them more suitable for investigating cognitive and perceptual correlates of driving safety and performance in healthy older adults or even younger adults in some cases. Research has primarily emphasized the relationship between driving outcomes and executive functioning, visuospatial ability, information processing speed, as well as attention.

There are, however, a few important caveats for interpreting this research. While cognitive domains are often discussed as discrete constructs, in actuality, many of them are strongly intercorrelated and they have even been conceptualized in a hierarchical manner (see (92) for a detailed discussion). For example, executive functions are seen as exerting high-level control over selective attention and the types of mental processing expected of individuals while performing some working memory tasks. Processing speed—seen as a low-level or "simple" domain—is important whenever task performance is evaluated by time-to-completion or even simply if stimuli are presented at fixed rates. It is not always clear to what extent differential performance on a test may be a result of impairment or normal variation in a higher or lower-level perceptual/cognitive ability or perhaps a mix depending on the individual or populations under study. There is still vociferous debate about whether or not certain cognitive domains ought to be divided into additional subdomains (93).

This lack of definitional clarity is reflected in the literature where many tests are presented either as a test of one cognitive domain or of another depending on the study in question. It is not unusual for a given cognitive test to be reasonably assignable to multiple different cognitive domains depending on what aspect of performing the task is highlighted. In more generous terms: many cognitive tests are integrative and can be understood to solicit multiple cognitive domains.

A related issue has to do with confusion about the use of the constructs themselves. For example: divided attention has been variably described as either set/task shifting (implying an overt shifting of attention with an executive component) or as a parallel processing mechanism (implying a lower level of pre-attentive perceptual processing). In other words, it is difficult (and some have argued impossible (94)) to conceive of a “pure” test of any particular cognitive domain—especially when the populations of interest rarely have the kind of very specific, very localized neurological insults seen in many of the most historically illustrative cases of neuropsychological assessment or in clinical models of particular cognitive functions.

Finally, performance on cognitive and perceptual tests is often more-or-less effective at predicting certain dimensions of driving, depending on the study in question: some tests may be effective at explaining either simulated or on-road driving performance, but fail to track closely with real-world reported crash involvement (and vice versa). These caveats should be kept in mind while reading the piecemeal treatment of different cognitive domains and perceptual skills presented in this survey of the literature.

Executive functions

Executive functions (EFs) have previously been defined as “processes that control and regulate thought and action” and are associated with the brain’s frontal lobes (95). As outlined by Miyake et al., these functions operate through and in concert with basic cognitive processes such as working memory (WM) and attention to achieve three primary goals: mental set, operation, or task shifting (“shifting”), inhibition of prepotent/automatic responses (“inhibition”), and information updating and monitoring (“updating”) (96).

It has been argued that incomplete or atypical maturation of the frontal lobes (and, thus, more limited EF) often seen in teenagers and very young adults might contribute to their tendency toward riskier, impulsive, and distracted driving behaviours (97,98). Research using transcranial direct current stimulation has supported this notion by showing that excitation of the dorsolateral prefrontal cortex in young adult males can lead to a more careful driving style in subsequent simulator scenarios (99). At the same time, one of the more influential theories in cognitive ageing research—the frontal ageing hypothesis—posits that age-related decline in cognitive tasks can often be attributed to decline in executive functions such as inhibition as a result of prefrontal lobe dysfunction (100). Thus, a number of studies have sought to evaluate how performance on a variety of laboratory and clinical tasks subserved by the main EFs contribute to driving safety in both younger and older adults.

Daigneault, Joly & Frigon studied performance on the Stroop Color and Word Test (Stroop), Wisconsin Card Sorting Test (WCST), and the Color Trail Test (CTT) between two groups of older adult males: one group that was accident-free and another group that had three or more accidents in the previous 5 years. The Stroop is a test of inhibition, attention and processing speed while the latter two are considered shifting tests. They found that the accident-free group performed significantly better on all three tests in terms of errors committed, were faster on the Stroop, and showed a possible trend toward being faster on the CTT (101).

Numerous studies have also investigated the Trail Making Test Part B (TMT-B) as a measure of shifting ability to see whether driving ability is related to performance on the task. One early study examining correlations between cognitive, visual-sensory, physical (i.e. range of motion), and visual-perceptual factors with on-road driving performance noted that, among the 40+ individual factors they studied, TMT-B was the one that was the most strongly negatively associated with an expert driving teacher's evaluations of driving skill (102).

Another study of over 3000 drivers aged 65 and older applying to renew their license also demonstrated a significant association between TMB and crash involvement in the 3-years prior to testing (103). A model constructed from their data predicted that drivers with the poorest performance on the TMT-B were roughly 1.5x more likely to experience a crash compared to those with the best performance. They found a similar result for part A of the Trail Making Test (TMT-A) which has been variably described as a test of information processing speed, visuomotor/visuospatial ability, and attention.

Adrian et al. had their participants perform a battery of cognitive tests of executive functions as well as an on-road driving test to explore, in depth, how these abilities were linked with driving performance (104). They performed partial correlations controlling for gender and age and found that shifting tasks such as TMT-B and the Plus-Minus task (a test of the average time to complete addition and subtraction problems when presented in block vs. alternating conditions) were positively associated with scores on a driving performance rating scale. Assessments were conducted retrospectively by a psychologist based on video recordings, objective driving metrics from the instrumented experimental car, logbook and co-pilot reports. Additionally, they found that the Operation Span task (a test of updating requiring participants to remember a growing list of words whilst simultaneously solving math problems) was also positively associated with these scores.

Although the authors did find relatively small correlations between driving performance and the aforementioned tests of executive functions, they found no such relationship with inhibition tasks such as the Stroop, Go/No-go, and Incompatibility test). Additionally, none of the cognitive measures were found to be significant predictors of driving performance in a subsequent regression analysis. By contrast, a study by Marotolli et al. found no relationship between TMT-B and self-reported adverse driving events in older adults (72). Despite inconsistencies in the literature, a meta-analysis by Mathias & Lucas suggests that the Trail Making Test (parts A and B) and the Stroop are good predictors of real-world driving problems such as crashes even if they aren't necessarily great predictors of on-road or simulated driving performance (105). In fact, the Canadian Medical Association primarily recommends administration of the TMT-B as part of routine screening by family physicians to evaluate older adult fitness to drive (106).

Interestingly, a recent review of research on the link between EFs and adolescent driving safety by Walshe et al. discusses how no link has been found between shifting and driving safety or performance in that population. They do, however, highlight the critical importance of adaptive behaviour and task switching while driving and go on to speculate that this lack of findings may be due to shifting ability maturing at a relatively young age or simply because it has only been rarely studied (107). Instead, they point to the importance of WM and inhibition measures in predicting young drivers' negative driving outcomes and suggest that dysfunction in these abilities may help explain why young drivers with developmental disorders such as attention deficit hyperactivity disorder (ADHD) are at an increased risk of crashing (108). While the authors did not focus on attention, they also speculate that levels of attention (e.g., sustained, divided, and selective attention) play a crucial role in driving safety. They lament how, while executive attention overlaps with the EFs that they were able to review, a critical lack of studies investigating attention's link to driving safety in young adults prevented them from achieving a more thorough synthesis.

Visuospatial ability

As discussed by Dickerson & Atri, visuospatial ability refers to a set of perceptual and cognitive skills including: "spatial navigation; perception of distance, depth, movement, and visual relations; visuospatial construction; and mental imagery" (109). Collectively, these skills allow us to "identify, integrate, and analyze space, and visual form, details, structure, and spatial relations." Considering that these are all seemingly critical in a highly visual task such as driving, the importance of visuospatial ability for driving safety and performance has a great deal of face validity. To that point, there is a fair amount of evidence showing that measures of these skills have value when it comes to evaluating the safety of cognitively impaired drivers.

Visuospatial function contributes to driving behaviours such as the correct positioning and maneuvering of a vehicle on the road and permits judging of distances between vehicles and to obstacles. Patients with certain types of dementia (e.g., Lewy body dementia and AD) or neurodegenerative conditions such as posterior cortical atrophy and corticobasal syndrome often exhibit deficits in these functions relatively early in the progression of their disease (110). Perhaps unsurprisingly, the majority of studies examining the link between these skills and driving have focused on individuals with dementia or cognitive impairment. Virtually all of them have focused on older adults.

A meta-analysis of 27 studies investigating the relationship between neuropsychological functioning and driving ability in dementia found that all the cognitive domains and perceptual skills they investigated were related to driving ability, however visuospatial skills were an especially robust indicator of across many different types of driving tests (111). In particular, it was one of the few sets of measures that remained significantly associated with driving performance even after removing studies with control groups from their analysis—a standard that is important to highlight if the intention is to use such measures in a clinical context to help identify cognitively impaired drivers that may still be fit to drive.

One study of healthy older adults also demonstrated moderate to strong correlations between visuospatial measures such as motion perception and the Paper Folding Test, and on-road driving performance (112). In fact, the motion perception test used—Ergovision Movement Perception—was shown to have the strongest effect size of all in a later meta-analysis of studies examining correlations between numerous perceptual and cognitive measures and on-road driving performance (105). Unfortunately, the aforementioned study was the only one investigating this test that was included in the meta-analysis. As such, it is difficult to know if this was merely an isolated finding as opposed to one that can be reliably replicated.

Another study compared older vs. middle-aged HIV-infected adults and further segmented participants in both groups by algorithmically designating some participants as cognitively impaired based on composite scores from a battery of cognitive tests they administered to them (113). Using hierarchical multiple regression, they found that visuospatial ability and attention each significantly predicted simulated driving performance in impaired older adults but not in impaired middle-aged or unimpaired older adults. Despite the fact that the study used a large battery of tests to assess 7 different domains of cognitive functioning (including executive functioning and information processing speed), no other domains emerged as significant predictors of simulated driving ability.

The contributions of visuospatial and other cognitive abilities to driving have also been studied in the context of multiple sclerosis (MS), due to the demyelinating nature of the disease (114). One such study of middle-aged MS patients used logistic regression to show that visuospatial learning and recall measured via the 7/24 Spatial Recall Test was the only predictor of collision and traffic violations out of a large battery of other neuropsychological tests (115). None of the other tests they studied, including: the TMT-B and tests of information processing speed; visual perception; language ability; and verbal learning were predictive of driving safety outcomes. On the other hand, processing speed emerged as the only significant predictor of performance on their on-road driving test.

Information processing speed and attention

In his book titled, “A theory of cognitive aging,” Dr. Timothy A. Salthouse discusses the information processing theory of cognition that continues to be widely influential even today. He hypothesizes that any number of age-related physiological changes (e.g., atherosclerosis impacting blood supply to the brain resulting in a decrease in the number of functioning neurons or age-related changes to white matter integrity affecting myelination and the speed of neuronal transmission) could impact the speed with which many cognitive operations can be executed through a process analogous to an increase in the level of noise in neural signals (116). Indeed, a general slowing down of action has been characterized as one of the most consistent behavioural observations in older adults (117). Naturally, this has been shown for mental tasks as well (118).

The robustness of findings regarding behavioural slowing and the discovery that age-related influences on cognitive measures can often be attenuated after statistical control of processing speed led Dr. Salthouse to develop a processing speed-centric theory of cognitive ageing situated within the broader cognitive information processing paradigm (119). The central conceit of this theory is that decreased processing speed is a major determinant of age-related declines in other cognitive domains and fluid cognition more generally. Processing speed has even been shown to mediate effects of depression and executive dysfunction on functional impairment in older adults (120). At the same time, processing speed has been conceptualized as a key component of attentional function given how frequently tests of attention include a speeded component (121).

Given the importance of processing speed in the gerontology literature, it should come as no surprise that it has also been heavily investigated by researchers studying older adult driving safety and performance. One way this has been done is via studies investigation reaction time (RT) in driving and driving-adjacent contexts. An advantage of RT as a measure is that it is intuitive to understand how reacting more slowly might translate to increased danger in many real-world driving scenarios.

As discussed by Hale et al., greater response latency with increasing task difficulty appears to follow a power law regardless of age group (122). However, the exponent of the best-fitting power function increases from young adulthood (20-25 years old), to late middle-age (50-60), and even further in older adulthood (65-75). Thus, while older adult processing speed deficits may not be obvious for simple RT tasks, more complex tasks carry a considerably greater relative penalty. This poses some problem for studying RT in driving where it might be attractive to assume that older adults will necessarily react more slowly to, say, the random presentation of a signal telling a participant to brake suddenly. Depending on how it's constructed, such a test may not represent a complex enough task to elicit much difference between age groups, except perhaps in cognitively impaired enough individuals.

This was precisely the result of a recent study examining the reaction times of drivers between the ages of 20 and 80 years old (123). They found that drivers of all ages navigating a practice track filled with road cones responded at comparable speeds when the only requirement was to brake as soon as a signal was presented. Once they introduced a dual task meant to divide the attention of their participants, a progressive increase in RT and RT variability was observed with increasing age. Interestingly, the highest-performing quarter of drivers over the age of 65 performed as well or better than the younger drivers—a finding that further reinforces the notion of heterogeneity in ageing outcomes and that challenges the notion of inevitable age-related cognitive decline.

Similarly, Wood et al. investigated whether a large, multidisciplinary battery of tests from visual, cognitive and motor domains could predict on-road driving performance in a sample of 270 aged 70-88 years old and found that reaction time was the key cognitive predictor (124). Of note, they used a series of five reaction time tests with progressively more demanding requirements that ultimately integrated divided attention and response inhibition demands on top of simple reaction time. While all the reaction time tests and many other cognitive tests (including the TMT-B) emerged as significant predictors, their most parsimonious regression model of participant driving performance included only complex reaction time requiring response inhibition as well as motion sensitivity. This result likely reflects that many of the cognitive tests they used are intended to measure similar cognitive domains (i.e., processing speed, attention, and executive functions) and, thus, probably ended up as redundant predictors of driving performance.

Reaction time aside, the poster child of much of the processing speed in driving literature is a test known as the Useful Field of View (UFOV). Following a long period of development starting in the 1980s, it has gone on to become among most extensively studied cognitive tests in the driving safety literature. The test is composed of three subtests, each layering on additional elements, to graduate from a "pure" test of processing speed via minimum display duration discrimination thresholds to one that also incorporates divided and selective attentional demands (see (125) for a detailed description and historical overview of the test).

One of the earliest studies with the UFOV investigating driver accidentology was a retrospective study of 53 participants between 57 and 83 years old using state-recorded accidents (75). They found that the UFOV was the single best predictor of driving accidents compared to visual function, eye health, and cognitive status. Of note, they used a binary categorical classification for UFOV performance instead of examining the scores themselves. Participants were grouped based on whether they failed all three UFOV subtests or if they passed any of the three subtests. Thus, the study could not distinguish which specific subtest(s) of the UFOV were most predictive and emphasized individuals with the most significant processing speed impairments. Individuals who failed the test were found to experience 4.2 times more accidents on average compared to those who passed and had over 15 times more accidents in intersections.

Another prospective cohort study examined 294 drivers aged 55-87 after a 3-year follow-up. The study found that a 40% or greater reduction in the extent of the useful field of view at baseline was associated with a more than 2 times greater likelihood to incur a crash at some point in the 3 years before follow-up after adjusting for age and other variables (54).

Another large prospective study of the role of visual factors in crash involvement has found that the second UFOV subtest (UFOV2) in particular, i.e., the divided attention subtest, was most strongly associated with increased crash risk relative to the other two subtests as well as visual sensory factors (59). The authors speculate that this result could be explained by the fact that, for their sample of 1801 drivers, the first subtest exhibited substantial floor effects[1] and the third

[1] "Floor" effect because UFOV scores are minimum display duration thresholds i.e., lower scores reflect better performance.

subtest (i.e., selective attention) exhibited ceiling effects. Supporting this notion is one study by Pietras et al. that tested the on-road traffic-entry judgments of a small sample of 20 older drivers divided into impaired and unimpaired groups based on the selective attention measure. Monte Carlo simulations generated from impaired participants' shorter time-to-contact and longer time-to-cross data suggested that these drivers were at a nearly 18x greater risk of crashing compared to the unimpaired group (128).

In addition to crash risk, studies have also explored how UFOV performance predicts on-road and simulated driving performance. Rizzo et al. studied simulated car crashes in drivers with AD and controls. They found that none of the control participants experienced any crashes while 29% of participants with AD experienced at least one crash (129). Additionally, AD subjects were twice as likely to experience near crashes. The strongest predictors of elevated crash risk were impairments in the UFOV as well as impairment in visuospatial and 3-dimensional structure-from-motion perception ability. Similarly, Cushman found that the UFOV was the single best predictor of on-road driving performance in a sample of 123 adults over the age of 55, including 32 participants referred from specialty clinics with suspected early AD (130). Using logistic regression, Myers et al. showed that UFOV was the single best predictor of whether drivers would pass or fail an on-road driving exam relative to multiple other tests of cognitive ability (131). Finally, Duchek et al. studied the association between on-road driving performance and composite UFOV scores in participants with very mild to mild AD as well as controls and found that they were moderately correlated with one another. They also showed that UFOV performance was inversely related to dementia severity.

While a substantial body of evidence suggests that UFOV and other tests such as the TMT-B could serve an important role in identifying at-risk drivers, research performing sophisticated sensitivity and specificity analyses suggests that any of these tests are likely insufficient as a stand-alone screening test for designating a driver as safe or unsafe. This is due to the finding that there is no optimal cut-off value that wouldn't result in either a large amount of false positives or else a large amount of false negatives (132). The authors conclude that even though the UFOV performed better than all the other instruments and measures they studied, a more integrative battery of measures combining the information provided by several different approaches is what is ultimately required. Thus, it would appear that there is still room to explore novel approaches to measuring cognitive, perceptual, and other functional abilities in the hopes of one day developing a more clinically useful screening test for older drivers.

While additional research is still required to resolve this limitation, there is another important application for cognitive testing that could potentially enhance driver safety without running the risk of unfairly restricting the privileges of drivers predicted to be at possible risk: rehabilitation. Some cognitive tests have been adapted into training paradigms with the goal of improving the underlying cognitive and perceptual abilities they test. Paradigms of this type are variably referred to as, "cognitive training," "brain training," or "perceptual-cognitive training" to highlight the complex interplay of perceptual and cognitive demands in specific training paradigms. For the sake of simplicity and a more generalized discussion, they shall hereafter all be referred to as cognitive training paradigms. The purported effectiveness of such training has been studied and there is now a substantial literature and spirited debate around the topic.

1.2 Cognitive training

1.2.1 What is cognitive training?

As has been discussed, perceptual and cognitive abilities can vary between individuals and across our lifespans. They are even seemingly modified within individuals across multiple time scales by factors like medication, education, diet, sleep hygiene, and exercise (133). Numerous tests are used to measure these abilities and the results of these assessments can have practical utility in the real world even if there is still uncertainty about the precise nature of many cognitive constructs. In light of these facts, researchers have begun to evaluate the comparatively ambitious hypothesis that targeted training may be able to enhance these abilities and may be able do so in a way that also has a significant beneficial impact on real-world outcomes—in other words, that the learning from cognitive training transfers to untrained tasks.

Different cognitive training outcome measures are often categorized by making reference to the notion of *distance* of transfer. As highlighted by Barnett & Ceci (134) while discussing transfer in a psychoeducational context, this concept has historically not been concretely defined. They argue that, as a result, the ongoing debate about whether "far" transfer is possible—i.e., transfer to tasks or abilities that are dissimilar to the training task—is plagued by misunderstandings between different groups of researchers. In their taxonomy of transfer, they attempt to provide some conceptual clarity by defining distance of transfer as the degree of (dis)similarity between two or more tasks on a variety of dimensions. They first distinguish between dimensions reflecting the *content* of transfer (i.e., a specificity–generality continuum describing *what* is transferred) and the *context* of transfer (i.e., *when* and *where* transfer happens) while emphasizing their embedded nature.

Zelinski (135), in an attempt to apply this framework to the literature on cognitive training, notes that transfer tasks used to assess the effectiveness of cognitive training are routinely measured using very different metrics than those used to track performance of the training task. Additionally, considering that many cognitive training tasks don't involve teaching of specific algorithmic processes—but, quite the opposite, often involve no specific strategy instructions—it is further noted that learning from such paradigms is frequently more general than specific.

The *when* and *where* of transfer—notions that most closely map on to how *distance* of transfer has classically been articulated—is composed of a number of dimensions describing: 1. the respective knowledge domains of each task (e.g., mathematical vs. linguistic problems); 2. their physical contexts (e.g., laboratory vs. ecological contexts); 3. temporal contexts (e.g., immediately following training vs. months following training); 4. functional contexts (academic vs. informal); 5. social contexts (e.g., individual vs. group training); 6. their respective modalities (e.g., visual tasks vs. auditory tasks). As two tasks increasingly diverge from one another in terms of these dimensions, transfer of learning from one to the other is increasingly described as *far transfer*.

Given the centrality of the automobile in many people's lives and the established link between cognition and driving, it is unsurprising that driving safety has been studied as a far transfer outcome for cognitive training. A basic rationale of such research can be stated as follows: if impairment in perceptual and cognitive abilities is the cause of increased driving risk, then recovery of those abilities should mitigate that risk and translate to improvements in driving performance. Cognitive training outcomes have also been studied in a wide variety of other contexts. While the promise of reversing, slowing, or even preventing age-related cognitive decline has been a major focus, research has also investigated whether such training may be beneficial for other populations as well. In addition to children and adults with neurodevelopmental, cognitive, or learning disorders, studies have investigated the potential of using cognitive training to enhance healthy adult and typically developing child cognitive functioning. Generally, cognitive training proponents claim that these improvements are possible, and long-lasting, due to neuroplasticity—a well-documented phenomenon describing how the brain is able to modify its structure and function even outside of critical developmental windows in response to experience (136).

Indeed, in a review of the cognitive training literature, Lustig et al. (137) approach the subject of transfer from a neuroscientific perspective. They focus heavily on studies that analyzed neuroimaging data from participants' performance of both training and transfer tasks and argue that such approaches are increasingly necessary to answer basic questions about cognitive training. In doing so, they marshal considerable evidence showing structural and functional changes to the specific neural substrates underlying performance on particular cognitive training tasks following training. Furthermore, they discuss research demonstrating successful transfer of cognitive training to untrained cognitive tasks shown to solicit overlapping neural substrate. One such study by Dahlin et al. (138) comparing younger and older adults found older adults recruited very different neural substrates to perform a letter-memory task. Ultimately, the older adults did not exhibit the same positive transfer to an untrained n-back task as young adults, but did start to exhibit patterns of brain activation closer to the young adults for performance of the trained task.

This result is consistent with the hypothesis that initial overlap in neural substrate underlying performance of two different tasks is required to observe transfer from one to the other. Thus, Lustig and her colleagues speculate that cognitive interventions are most likely to exhibit transfer to tasks to share common neural processing. Additionally, interventions in older adults might offer a degree of long-term protection against dysfunction even if beneficial transfer isn't always apparent after short training durations. It remains unclear whether simply extending the training duration or adapting the training protocol in some other way might have ultimately resulted in similar transfer in older adults. Another implication is that far transfer may indeed be possible if the outcome in question solicits some overlapping neural substrate to the training task. This precondition may help explain the relative paucity of studies demonstrating successful far transfer even when near transfer is commonly reported (140).

1.2.2 The evidence for cognitive training benefits

Before reviewing this literature further, it is important to point out that, historically, much of this research has been conducted by organizations with a vested interest in demonstrating beneficial outcomes. In some instances, the results of this research have been exaggerated by marketing departments in order to help sell the commercial versions of cognitive training programs. There is a clear financial incentive for them to do so: in 2015, SharpBrains—a market research firm specializing in the health and performance applications of brain science—forecasted that the "digital brain health market" (a market segment including evaluation and training technologies) would grow to $6.15 billion in yearly sales by 2020 from ~$1 billion in 2012 (141). Recent market research forecasts that the ongoing demographic shift will push this market to a total value of $11.4 billion by 2027 (142). Many adults alive today will no doubt recall Lumosity—a computerized "brain training" software platform that was heavily marketed on television, radio and the internet—and its claims that customers could perform better at work and school or ward off dementia by simply playing games designed to solicit specific cognitive domains. The company that created Lumosity, Lumos Labs, Inc., was sued in 2016 by the U.S. Federal Trade Commission for deceptive marketing and lost (143). This resulted in them being ordered to pay a $50 million fine that was ultimately settled by paying $2 million in redress and by changing their marketing practices.

Even prior to this high-profile lawsuit, many within the scientific community expressed doubts about cognitive training. Healthy skepticism is a key feature of scientific inquiry—a point elegantly captured by the Sagan standard that "extraordinary claims require extraordinary evidence." It is within this spirit that the Stanford Center on Longevity and the Berlin Max Planck Institute for Human Development issued a joint statement in 2014 highlighting the need for additional systematic research in order to replicate, clarify, consolidate and expand upon existing evidence for the benefits of cognitive training (144). They concluded that there was no compelling scientific evidence to believe that brain games can reduce or reverse cognitive decline.

Shortly thereafter, a group of 133 scientists and therapists rebutted this and other claims made in the joint statement by publishing an open letter on the website Cognitive Training Data. There they noted that not all brain/cognitive training paradigms are equivalent in terms of their claims and evidence-base. They strongly agreed that "claims promoting brain games are frequently exaggerated, and are often misleading" and "many companies that claim to provide brain fitness have not subjected their exercises to peer-reviewed trials to show any efficacy." On the other hand, they emphasized the large body of well-controlled, peer-reviewed evidence supporting lifelong brain plasticity and the efficacy of particular cognitive training programs as measured by real-life indices of cognitive health (145). Among these 133 signatories were several directly involved in developing the UFOV—an assessment instrument whose use as a cognitive training paradigm has also been thoroughly investigated.

For the sake of brevity, this introduction will focus primarily on the body of evidence for the aforementioned UFOV training paradigm (i.e., speed-of-processing training)—now licensed and integrated into commercially available software called BrainHQ by Posit Science—due to its relative breadth and its regular usage of driving safety and performance outcomes. The cognitive training literature is vast and numerous programs (both computerized and non-computerized) have been developed over the years with the goal of improving various aspects of human brain function. Furthermore, this introduction will not discuss the literature reporting cognitive benefits of playing action video games either as a hobby or as part of a dedicated intervention (146,147). Readers interested in a more thorough critical review of the wider cognitive training literature are recommended to read (141).

1.2.2.1 Benefits of speed-of-processing (adapted UFOV) training

Early studies

Rather than simply hone in on the display duration thresholds at which participants are able to perform UFOV subtasks, studies incorporating speed-of-processing training have generally made use of an adapted version of the UFOV assessment software. As described in one such study by

Edwards et al. and briefly summarized here, the training paradigm first requires participants to practice with variations of the first UFOV subtest at gradually increasing speeds until they become capable of making reliable discriminations and detections at the shortest target durations (148). Participants then progress to practice using tasks involving simultaneous central and peripheral detections and discriminations which solicit divided and selective attention much like UFOV subtests 2 and 3. In this study, training continued until participants either reached a specific predetermined performance criterion or ten sessions were completed.

Their results demonstrated that this form of training transferred not only to the original UFOV assessment test, but also to speed on timed instrumental activities of daily living (Timed IADL) meant to resemble everyday activities such as finding a specific telephone number in a directory, counting out correct change, finding and reading information from food and medication labels, etc. While transfer to several other tests of speed-of-processing was evaluated, none of these exhibited any significantly improved performance relative to controls. As expected by the authors, no significant transfer was found to performance on tests intended to measure other cognitive domains. They also noted that the relatively small magnitude of improvement they observed compared to earlier studies may have been a consequence of their decision to include normal participants instead of only participants determined to have speed-of-processing impairment.

One early study of UFOV and transfer to driving performance compared speed-of-processing with simulator-based driving training and found that both forms of training enhanced different aspects of driving performance (149). The speed-of-processing training improved UFOV performance, resulted in significantly improved performance on a complex reaction time task, and significantly reduced the number of hazardous maneuvers made during a follow-up on-road driving evaluation. By comparison, the simulator-based training produced improvements in information-based driving skills such as appropriate use of turn signals and relative vehicle positioning during stops. Interestingly, these improvements were found to endure at an 18-month follow-up test.

The Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) Study

To date, the Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) study is the largest investigation into the long-term potential benefits of speed-of-processing, memory and reasoning training interventions on a variety of outcome measures. It was a prospective study conducted at six different field centers throughout the United States that ultimately enrolled roughly 2,800 participants and featured multiple follow-ups across the study's ten-year duration. Additionally, the study followed many of the best practices for clinical trials, including: random group assignment with controls, ethnic and geographic diversity in sampling, systematic screening for a wide variety of conditions and functional impairments, and the use of Consolidated Standards of Reporting Trials (CONSORT) flow diagrams at every stage throughout the study. It did not, however, feature an active control group.

A subset of participants was also given booster training sessions, allowing for some insight into the effects of increased "dosage" of cognitive training. Proximal outcomes that were invested included measures of cognitive abilities. Primary outcomes included subjective and performance-based measures of daily function. Finally, secondary outcomes were a set of health-related quality of life measures (SF-36 scales) as well as long-term driving outcomes such as self-reported driving behavioural outcomes and state-recorded collisions.

The findings for proximal training effects were consistent with the results of earlier studies: each of the three different interventions resulted in improvements in the trained domain alone that was durable at two-year follow-up (150). This effect was strongest for speed-of-processing and reasoning training. The booster sessions of training further enhanced gains as well as the durability of these gains. No group differences were detected on primary outcomes at this stage, but the authors noted that this could have been due to the fact that very little functional decline was observed for the sample overall.

While some training gains were lost by the five-year follow-up, the improvement in the trained cognitive domains remained statistically significant—especially for the speed-of-processing group and in subjects that received booster sessions (151). All three cognitive training groups reported less subjective difficulty with IADLs compared to controls, although this was only statistically significant in the reasoning training group despite similar effect sizes in the other two intervention groups. After controlling for differences in baseline age and cognitive function, participants in the speed-of-processing group that attended booster sessions exhibited significantly improved performance in a test of everyday speed-of-processing. Once again, the authors interpreted these results as promising but also likely limited by the temporal lag between normal age-related cognitive decline and the onset of functional impairment.

By the ten-year follow-up, it was found that only reasoning and speed-of-processing training gains endured (152). Interestingly, despite the fact that memory training did not seem to endure, self-reported difficulty with IADLs was lower for all three training groups compared to controls. No significant improvement was reported on the performance-based measures of everyday functioning. In their discussion, the authors speculated that cognitive training may have produced changes in either social interaction behaviours or in long-term patterns of neural activation that resulted in greater ease in IADLs even in situations where cognitive effects could no longer be detected i.e., for memory training. The fact that these effects were merely modest at best was explained by the multifactorial nature of functional impairment. Finally, they attributed the lack of effect on performance-based measures to be reflective of the fact that the measures they selected had more in common with multi-ability cognitive tests than actual acts of daily living. It is possible that repetition of all the outcome measures at multiple follow-up sessions could have introduced practice effects that resulted in an underestimation of age-related declines. Ultimately, it is impossible to rule out that these differences may have merely been placebo or demand characteristic effects due to the lack of an active control group. That being said, a later study showed that the group trained on speed-of-processing training exhibited up to a 29% decrease in risk of developing dementia at the ten-year follow-up compared to controls (153). Interestingly, the same was not true for either memory or reasoning training. Sensitivity analyses for the effect of training sessions revealed that the participants who received booster training sessions had the lowest risk overall.

Wolinsky et al. reported on health-related quality of life measured via eight 36-item scales and found that speed-of-processing training but not memory or reasoning training resulted in less clinically significant extensive quality of life decline (defined as a drop of ≥0.5 standard deviations from baseline on four or more of the eight scales) at the two-year follow-up (154). While speed-of-processing training provided the greatest benefit overall, all three of the interventions offered some protection against this level of decline relative to controls by the five-year follow-up period. Similarly, speed-of-processing training was found to decrease the risk of experiencing clinically important increases in depressive symptoms measured by the Center for Epidemiological Studies-Depression scale (CES-D) by roughly 30% at both one-year and five-year follow-ups (155). Notably, this effect was not observed for the reasoning and memory training groups which reinforces the interpretation that speed-of-processing training (rather than a potential confound such as social contact) was responsible for the effect. A more recent study of older adults living independently and in assisted living conditions did not replicate this finding, however (156). In fact, they found only an unexplained increase in depressive symptoms for older adults in assisted living conditions one year after training.

Speed-of-processing and reasoning (but not memory) training were found to result in decreases to state-reported at-fault collisions per person mile driven on the order of about 50% in the six years following training relative to controls (157). Of note, the association for reasoning training was only statistically significant after controlling for the effects of several covariates whereas the effect was significant for speed-of-processing training in both adjusted and unadjusted models. A curious result from that study is that overall crash rates did not appear to differ between groups—suggesting that the intervention groups experienced more accidents where they weren't judged at-fault compared to controls. Based on this, Simons et al. (2016) criticized the interpretation that the interventions had any benefit as misleading and attributed the observed decrease in at-fault crashes to statistical noise resulting from the overall low number of crashes reported (141). Still, another pair of studies using an ad hoc dataset combining ACTIVE and Staying Keen in Later Life (SKILL) study data showed that drivers with impaired baseline UFOV performance that completed speed-of-processing training had a 40% decreased likelihood to cease driving in the three years following training (158) and also reported less decline in subjective driving ease, exposure to challenging driving situations, and the extent to which participants drove beyond familiar surroundings i.e. "driving space" (159). One potential limitation highlighted by the authors of these studies has to do with the fact that they did not use intention-to-treat analyses. Instead, they only analyzed data from participants that completed a minimum of eight out of a possible ten training sessions and who were determined to be at-risk for future mobility declines according to baseline UFOV scores.

This was addressed in a later study by Ross et al. that performed both intention-to-treat and dosage analyses on the ACTIVE study sample to examine changes in participants' driving mobility five years following training (160). Another improvement made to the analysis was the use of the memory training group data as an active control group alongside the no-contact control group. While the intention-to-treat analyses were not significant, the authors reported a dose-response effect whereby increases in self-reported driving frequency across five years were greater with additional sessions of training. There was no association with driving exposure except in subsequent subsample analyses of participants with low baseline UFOV scores. No associations with driving space were detected. The authors concluded by highlighting that while the effect sizes they reported were small, the fact that they were significant and durable at all across five years with relatively small "dosage" lends support to continued investigation into the use of speed-of-processing alongside other cognitive and physical training programs as a form of mobility intervention.

The Iowa Healthy and Active Minds Study (IHAMS)

The Iowa Healthy and Active Minds Study (IHAMS) sought to improve on some of the limitations of the ACTIVE study by expanding its inclusion criteria to include adults between the ages of 50-64 as well as by including an active control group required to complete crossword puzzles. It used commercially-available software modelled after the UFOV task as its experimental treatment task. Additionally, the study compared the effects of supervised, on-site training with self-administered at-home training and also included a subgroup of participants that received supervised booster training. The results of the study are discussed in two papers. The first of these only examined the immediate effects of training on UFOV performance and, unsurprisingly, found that all the groups that received speed-of-processing training exhibited improvement on the near-identical UFOV task (161).

The second study reported on whether this effect persisted at a one-year follow-up and also assessed whether transfer to a number of neuropsychological tests occurred (162). Whereas the active control group exhibited a decline in UFOV performance relative to baseline at follow-up, both of the speed-of-processing training groups were protected from this decline. The subgroup that received two 2-hour sessions of booster training roughly a month before the follow-up was the only one that still exhibited improved UFOV performance relative to baseline. Small but significant transfer effects to some of the secondary neuropsychological task outcome measures were detected for all the speed-of-processing training groups. Specifically, these groups improved on the TMT-A, TMT-B, Symbol Digit Modalities Test (SDMT) and Stroop Word subtest. The TMT-B—though often discussed as a test of set-shifting—is a timed test and has been argued to solicit speed-of-processing and attention much like the TMT-A. The SDMT is believed to depend on divided attention and processing speed once again due to a time component. Finally, while the Stroop is generally used as a test of executive functions such as inhibition, research has suggested it can be used to test processing speed (163). In this case, only the first congruent condition subtest (typically held to measure reading speed) exhibited any transfer. The two tests that didn't exhibit any improvement were the Digit Vigilance Test and the Controlled Oral World Association Test—the former being a test of sustained attention and psychomotor speed while the latter is a test of verbal fluency. These findings are consistent with the broader cognitive training literature suggesting that training in one cognitive domain does not typically transfer to other domains. It also elicits questions about how different experimenters define the particular modalities a given cognitive test measures.

Interestingly, no significant differences in standardized effect sizes were found between middle-aged (50-64) and older adults (65+) for the outcome measures. This suggests that the training was equally effective for the younger age group and means that even younger adults might see benefits from cognitive training. Additionally, no significant differences on secondary task outcomes were detected for the booster training group—perhaps because of the relatively short temporal delay between baseline and follow-up assessments. Unfortunately, the study did not evaluate whether any transfer might have occurred to relevant real-world tasks such as driving performance and safety.

In summary, there is limited but compelling evidence for the benefits of speed-of-processing training. The most robust finding is that performance on assessment tests can be improved through practice or training on structurally similar tasks. Furthermore, this training has been shown to transfer to structurally dissimilar tasks meant to measure the same underlying cognitive domain in some studies but not all of them. It may improve everyday cognition in a way that translates to an improved sense of quality of life and ease with activities of everyday living but this result may also reflect demand characteristics or placebo effects. That said, such training does not improve general cognition in a way that translates to untrained cognitive domains. Finally, some evidence suggests that cognitive training improves driving safety and reduces the risk of driving cessation in ageing adults. While the body of evidence is of debatable consistency and strength to support many of the marketing claims made by Posit Science, it certainly justifies continued investigation.

1.2.2.2 3-dimensional multiple object tracking (3D-MOT): a dynamic and integrative alternative to UFOV

What is 3D-MOT?

Numerous other computerized cognitive training programs other than UFOV have been developed over the years. 3-dimensional multiple object tracking (3D-MOT) is one such program. 3D-MOT is based on the MOT task developed by Pylyshyn & Storm to evaluate their FINST theory (FINgers of INSTantiation) that posits the existence of a preattentive mechanism for “pointing to” and indexing multiple objects of interest in a visual display (164). The theory proposes a two-stage model whereby a fixed number of these pointers/indexes (usually four) are processed in parallel for tracking and subsequently allow serial attention to efficiently switch between the objects they are attached to for the sake of tracking changes in their properties. Later research highlighted limitations with the purely low-level parallel mechanism for tracking and instead proposed mixed models implicating more effortful higher-level cognitive abilities such as working memory and serial attention (165,166). In these models, working memory and serial attention are either used alongside the parallel tracking mechanism to help resolve intermixing between targets and distractors or else the parallel tracking mechanism is dropped entirely in favour of multicomponent working memory alongside attentional control (167). Indeed, the involvement of working memory processes during tracking has been evidenced by neuroimaging and electrophysiology measurements conducted while participants perform MOT (168,169).

Interestingly, other studies have even challenged the idea that attention must operate in a purely serial fashion and have proposed that attention can be deployed multifocally even without the existence of a limited number of preattentional indices (170,171). Still, more recent data seem to reinforce serial sampling models by showing that manipulating the temporal frequency demands of the tracking task through the addition of extra distractors sharing a target's trajectory (as opposed to simply increasing displacement speed or number of targets to track) causes an inversely proportional decrease in tracking ability (172). Recent research has attempted to synthesize these contradictory findings by suggesting that parallel/multifocal and serial tracking mechanisms exist simultaneously and are used at different times by the visual system depending on whether low-resolution information is sufficient or high-resolution information needs to be sampled (173).

While the debate surrounding how to model MOT ability is hardly resolved, multiple studies now suggest that tracking is not limited by a fixed resource and can instead be flexibly divided between upwards of ten objects provided they are all moving slowly enough (166,174). Such research suggests that MOT is subserved by a limited but flexible, possibly multifocal attentional mechanism (175). Suffice it to say that MOT has become a highly influential paradigm for studying the nature of dynamic visual attention.

3D-MOT builds on the classic MOT paradigm most obviously by the addition of stereoscopic 3D and the ability for the objects to move in 3D space. In addition to increasing the naturalism of the task, the addition of depth cues has been shown to increase tracking speeds (176)—a finding that is in line with other research showing that stereoscopy improves natural task performance (177). Its use as a training and assessment program is implemented in commercially available software known as NeuroTracker. The details of this implementation reveal another significant difference between 3D-MOT and many experimental uses of MOT: the use of adaptive staircase speed thresholds to quantify variability in individuals' performance and improvement (176).

In its most typical form, 3D-MOT requires the simultaneous tracking and subsequent correct identification of the entire subset of four moving spherical targets among four identical moving distractors for a period of eight seconds. While moving, the eight objects interact with each other in a dynamic fashion e.g., bouncing off each other following collisions or simply occluding one another in 3-dimensional space. 3D-MOT is similar to the UFOV2 subtest in that it requires participants to spatially distribute or divide their attention across multiple targets. It is also similar to the UFOV3 subtest given that it requires participants to selectively attend to targets while inhibiting distractors. It differs in several important ways, however. Aside from the 2D-3D distinction, one of the most notable differences is that 3D-MOT is less dependent on preattentive processing. It instead requires participants to dynamically allocate attention to both track targets and engage in visuospatial processing to resolve interactions between objects. Furthermore, the extended length of a typical trial necessitates sustained attention in addition to more top-down executive attention and working memory demands. Speed-of-processing is implicated at this stage due to the need to quickly and efficiently process visual information related to the interactions between targets and distractors, especially at faster object displacement speeds.

3D-MOT does not measure minimum display duration thresholds, unlike the UFOV. Instead, 3D-MOT measures the maximum displacement speed threshold at which participants can successfully track all the targets simultaneously. Research has demonstrated that both movement speed and number of targets are key parameters affecting the difficulty of the task (178). As a result, the test is highly adaptive: both displacement speed and the number of targets to be tracked can be modulated to accommodate various levels of ability. Thus, the test is less susceptible to ceiling effects ("floor" effects for UFOV) when testing non-impaired and young individuals and can also have its complexity scaled down to test individuals with various levels of cognitive decline. Thus, 3D-MOT may offer several advantages over UFOV as an integrative test of cognitive function: it tests the brain's ability to process visual information in a complex dynamic scene; it solicits a greater spread of cognitive functions; and, finally, it may offer greater sensitivity in young and healthy populations.

The use of 3D-MOT as an assessment paradigm

The use of 3D-MOT as an assessment tool in a wide range of populations is well-established at this point. One of the earliest studies using the task demonstrated that elite athletes possess a measurable baseline advantage at the task and are also able to improve their tracking speeds more rapidly compared to more amateur elite athletes and non-athletes—suggesting that this population has superior perceptual and cognitive skills compared to average (179). Such skills are of obvious importance in highly dynamic team sports: the careers of transcendent athletes like Larry Bird and Wayne Gretzky—both lauded for their superior anticipation and perception during gameplay—clearly demonstrate the difference these talents can make. To that point, higher baseline tracking performance has been associated with improvements in independently-published measures of on-court performance in NBA players (180), running distance during a collegiate-level Rugby match (181), and upper as well as lower body reaction times in collegiate-level female soccer players (182). Similar results have been found for the baseline tracking ability and performance on other cognitive tests of visual spatial memory as well as selective and sustained attention in professional vs. amateur video game players (183). Interestingly, 3D-MOT ability has also been related to measures of surgical performance (184).

In addition to elite performance contexts, the paradigm has also been successfully used as an assessment in developmental, medical, and ageing contexts. Tullo, Faubert & Bertone compared 3D-MOT tracking performance in school-aged (6-12), adolescent (13-18) and adult (19-30) groups to investigate how the cognitive capacities underlying tracking performance develop from childhood into adulthood (185). They found that tracking thresholds were significantly lower in the youngest group but that the magnitude of this difference was lower compared to results from similar 2-dimensional tracking paradigms.

Another study compared 2D vs. 3D as well as concussed vs. healthy learning and youth vs. young adult vs. older adult learning functions (186). They found, once again, that participants in the 3D environment outperformed those in the 2D condition and that switching from 3D to the 2D environment was detrimental to learning. Both older adults and concussed individuals exhibited lower baseline tracking ability. Interestingly, the concussed group also exhibited a higher rate of learning despite a lower baseline. Other research has shown that the learning function of 3D-

MOT is totally disrupted or impaired in the immediate days following a concussion (187) but that training gains eventually become identical to those of controls (188). This apparent contradiction may be due to sampling differences: participants in the first study were defined as recently concussed if the injury occurred within the previous ten days. Additionally, half of the included subjects were defined as "prolonged concussed individuals" and had reported symptoms for up to six months following their injury. The results of these and similar studies suggest that 3D-MOT may have value as a way to monitor and manage mild traumatic brain injury. The finding that older adults start at a lower baseline has been previously demonstrated but research also suggests that older and younger adult learning functions are equivalent (189).

The use of 3D-MOT as a cognitive training paradigm

Like the UFOV, 3D-MOT has also been investigated as a cognitive training paradigm. In addition to aforementioned studies comparing how different populations improve at the task itself with practice, a number of studies have investigated how training gains may transfer to performance on other cognitive tests and more naturalistic tasks. Sports performance is a recurring theme.

One study of university soccer players investigated whether ten sessions of 3D-MOT training would improve passing, dribbling, and/or shooting decision-making skills compared to both a passive and an active control group made to watch 3D soccer videos (190). They used a standardized instrument to assess these skills with an experienced rater who was blinded to the experimental protocol. Additionally, they analyzed players' subjective judgments about their global decision-making on-field. It was found that the experimental group improved in their independently-rated passing decision accuracy compared to controls. This improvement was also seemingly reflected by a proportional increase in subjective confidence levels for decision-making accuracy. On the other hand, another study on transfer in volleyball experts only found transfer of training to unrelated sustained attention and processing speed measures with no improvement in a volleyball-specific decision-making task (191). Similarly, a study on game performance among basketball players showed that training only produced improvements on a measure of concentration and did not affect game performance statistics relative to controls (192). This mixed pattern of results underscores the difficulty in measuring transfer of cognitive training to real-world outcomes whose performance is usually determined by many factors beyond cognitive functioning.

Research has primarily focused on cognitive outcomes of 3D-MOT training. Parsons et al. studied university-aged adults and showed that, relative to a passive control group, 3D-MOT training resulted in enhanced attention, visual information processing speed, and working memory (193). They also showed changes in resting-state quantitative electroencephalography (qEEG) suggesting improved attention consistent with attentional theory. Other studies are largely consistent in reporting beneficial transfer to working memory (194,195) and attentional abilities in children and young adults (196). A number of studies conducted with older adults further suggest that training can improve performance on measures of selective attention, psychomotor speed, working memory, processing speed, reaction time, cognitive flexibility (197–199) as well as biological motion perception (200). Like with the UFOV, this mixed pattern of results highlights the need for further research into whether such improvements ultimately translate to the real world.

Can 3D-MOT be used to predict and enhance driving safety?

Despite the established literature for UFOV and driving, 3D-MOT is a newcomer in this space. Only two other studies have explored the relationship between driving outcomes and tracking ability. Woods-Fry et al. investigated simulated driving performance in a sample of 30 older drivers and found that baseline 3D-MOT performance was strongly negatively associated with measures of uncontrolled and risky driving such as lane deviation and crashes (201). Bowers et al. showed that low scores on their own implementation of a brief 2-dimensional MOT test were significantly associated with driving errors and moderately correlated with UFOV performance, but did not enhance a predictive model when included alongside UFOV subtest 2 (202). The link between 3D-MOT training and UFOV performance is equally underexplored. Only one paper—a pilot study in exclusively middle-aged adults with multiple sclerosis—has investigated this question and demonstrated that training on the former transfers to performance on the latter (203).

As has been established, 3D-MOT is capable of assessing and enhancing cognitive ability in a manner similar to UFOV. Considering that UFOV and 3D-MOT seem to tap into a number of overlapping cognitive domains, one might expect that 3D-MOT training should transfer to speed-of-processing or attentional ability as measured by UFOV. It is also reasonable to wonder if the more dynamic and integrative form of training seemingly offered by 3D-MOT can replicate the successes of the UFOV when it comes to predicting and enhancing driving behaviour. While the current body of literature hints at this possibility, more evidence would provide convergent validity for the claims of both these programs.

It is as-of-yet undetermined how cognitive assessment can and should be used to supplement currently insufficient assessments of driver safety. Additionally, it is still unclear if cognitive training can enhance *any* complex real-world behaviours—let alone those related to driving performance. Michon's (204) process-based, hierarchical model of driving considers that it is composed of a number of different behaviours decomposed into various levels that can be seen to solicit a wide array of brain circuits: top-level strategic processes such as path planning, middle-level tactical processes such as adapting to other drivers, and low-level processes involved in action execution and perceptual processing. This lowest level in particular represents a reasonable target for cognitive training interventions such as 3D-MOT and UFOV that propose highly generalized improvement of attentional processing and information processing speed. By comparison, educational alternatives such as defensive driving or driving theory courses can be understood as representing cognitive interventions aimed at these higher-level strategic and tactical processes.

While comparatively few studies have looked at neural correlates associated with the lowest level in the context of attentionally-demanding driving, those that have find activity in multiple neural systems such as fronto-parietal, cingulate, and cerebellar networks frequently associated with visual attention, integration of visual information, processing of visual motion, and attentional control (205,206). Neuroimaging studies conducted during 2D-MOT have demonstrated that numerous fronto-parietal areas are implicated in a load-dependent (i.e., related to the number of targets to be tracked simultaneously) fashion during tracking (207). Additionally, a recent study by Karthaus, Wascher & Getzmann (208) compared EEG signals of older and younger adult drivers and found that differences in brain activity between older drivers could be associated with differences in their lane-keeping variability during a crosswind condition. While older adults exhibited decreased brain activity and reaction times relative to younger adults consistent with the hypothesis that they were less efficient at allocating attentional resources, the subgroup of older adults with high driving lane variability while compensating for the crosswind exhibited increased frontal Theta—a finding that the authors interpreted as indicative of higher mental workload for the task for this subgroup relative to the other older adults. They interpreted this difference as reflecting two alternative driving strategies where lower Theta reflected a more proactive and alert driving strategy. Intriguingly, frontal Theta has been shown to decrease sharply during the tracking phase of 3D-MOT trials, possibly reflecting an overlapping attentional process meant to maintain vigilance (209). Furthermore, training with 3D-MOT has also been shown to decrease resting-state fronto-parietal Theta activity (193). Thus, there does appear to be a plausible mechanism for 3D-MOT training to improve aspects of low-level driving performance via shared neural mechanisms and substrates.

Given the centrality of driving in modern life, the massive projected increase in older adult drivers in the near future, and the tantalizing possibility of improving cognitive function and driving safety for all age groups, there is a clear impetus for focused research into these matters. The current research project aims to address this knowledge gap.

1.3 Objectives and hypotheses

The primary aims of the present thesis are to explore: 1. whether cognitive assessment via 3D-MOT can be used to predict driving performance, 2. whether cognitive training via 3D-MOT transfers to UFOV as a cognitive measure related to driving safety, and 3. whether cognitive training via 3D-MOT transfers to objective measures of driving performance. To do so, two studies were conducted: the first of these addressed the first question while the second addressed the latter two. These studies addressed the link between cognitive ageing, differential training outcomes, and driving behaviour by comparing young and older adult participants.

Study 1: Predicting driving performance with 3D-MOT (Article 1)

As a first step to investigating whether 3D-MOT training might improve driving performance, it is first necessary to understand what aspects of driving performance baseline tracking ability best predicts. To do so, this cross-sectional study sets out to first validate a methodology for assessing simulated driving performance via custom driving scenarios and novel objective driving metrics via exploratory analyses. An additional consideration was determining which scenario features would elicit the most natural driving behaviour across various age groups. Three custom scenarios were designed to each impose different levels of cognitive load by virtue of differences in their road layouts and traffic densities. Each scenario was constructed with several dangerous surprise events that necessitated participants to take defensive measures while driving to avoid collisions. Hierarchical correlation analysis between driving metrics and ANOVAs comparing different age and driving experience groups were conducted to determine which metrics provided the most relevant, non-redundant information as well as which scenario(s) were the most well-suited for eliciting differences in driving behaviours shown to be characteristic of each group by the broader literature.

Following these analyses, we investigate whether baseline 3D-MOT predicts simulated driving performance. It was expected that 3D-MOT would predict aspects of driving performance given the existing literature showing as much for other cognitive tests. The cross-sectional design of the study and use of an instrumented simulator permitted correlation and multiple linear regression analysis comparing the relative contributions of cognitive ability, mean driving speed, and age in predicting adverse driving outcomes such as crashes, near crashes, the distance at which participants responded to dangerous events, and the intensity with which they responded to these events.

Study 2: Enhancing driving performance with 3D-MOT (Articles 2 & 3)

The second experiment examines whether gains made during ten sessions of 3D-MOT training transfers to UFOV ability and simulated driving performance. Young and older adults were compared to shed light on how ageing might impact learning and transfer.

In the first of two articles, we examine whether 3D-MOT training transfer to young adult UFOV performance compared to an active control group trained on a combination of a low-level perceptual discrimination task and a puzzle video game. We hypothesized that the group trained on 3D-MOT—but not the active control group—would improve on the untrained UFOV task due to enhancement of shared cognitive processes following training. ANCOVA analysis controlling for pre-training performance was conducted to compare the two groups following training. Older adult subjects were omitted from this article due to the global COVID-19 pandemic interfering with recruitment as it was being prepared.

In the second of two articles, we compared post-training driving performance between a group trained on 3D-MOT and one trained the aforementioned perceptual discrimination and puzzle video game tasks. Both younger and older adults were included in both groups in order to investigate if and how there would be differential effects of training. It was expected that 3D-MOT training would produce beneficial transfer to driving performance given past findings showing that cognitive ability predicts driving performance and because UFOV training has been shown to improve simulated driving performance. Furthermore, we hypothesized that this effect should be more prominent in older adults considering their lower baselines for 3D-MOT ability. Correlations were computed to understand how the driving metrics related to 3D-MOT ability post-training. ANCOVA analyses controlling for pre-training performance were then conducted to determine if driving performance differed between groups following training. Age was also included as a factor to see whether it had an impact on transfer. Finally, UFOV scores were analyzed to gain a deeper understanding of the differential outcomes of training.

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Article 1 – Driving simulator scenarios and measures to faithfully evaluate risky driving behavior: A comparative study of different driver age groups

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Abstract

To investigate the links between mental workload, age and risky driving, a cross-sectional study was conducted on a driving simulator using several established and some novel measures of driving ability and scenarios of varying complexity. A sample of 115 drivers was divided into three age and experience groups: young inexperienced (18-21 years old), adult experienced (25-55 years old) and older adult (70-86 years old). Participants were tested on three different scenarios varying in mental workload from low to high. Additionally, to gain a better understanding of individuals' ability to capture and integrate relevant information in a highly complex visual environment, the participants' perceptual-cognitive capacity was evaluated using 3-dimensional multiple object tracking (3D-MOT). Results indicate moderate scenario complexity as the best suited to highlight well-documented differences in driving ability between age groups and to elicit naturalistic driving behavior. Furthermore, several of the novel driving measures were shown to provide useful, non-redundant information about driving behavior, complementing more established measures. Finally, 3D-MOT was demonstrated to be an effective predictor of elevated crash risk as well as decreased naturally-adopted mean driving speed, particularly among older adults. In sum, the present experiment demonstrates that in cases of either extreme high or low task demands, drivers can become overloaded or under aroused and thus task measures may lose sensitivity. Moreover, insights from the present study should inform methodological considerations for future driving simulator research. Importantly, future research should continue to investigate the predictive utility of perceptual-cognitive tests in the domain of driving risk assessment.

Introduction

Early versions of driving simulators date back to 1934 (1) but their practicality has been limited. Recent advances in technology allow researchers and therapists access to a new generation of affordable, realistic and sophisticated simulators. As a result, investigations into driving behavior have significantly increased. Compared to on-road driving studies, the virtual environment of a driving simulator provides several advantages. Chief among these is that participants' reactions to potentially life-threatening driving situations can be evaluated in perfect safety. Driving simulators allow researchers to reliably control, standardize and replicate specific driving events and conditions, such as route difficulty, traffic, weather, in ways that are simply not possible with on-road study designs that use open (i.e. public roads) or closed roads (specially designed closed circuits) (2,3). Moreover, driving simulators allow researchers to collect and process a wealth of objective, performance-based data in a relatively short time. Despite these many advantages, designing driving-simulator based studies is not without its challenges. In the context of flight simulators, Blickensderfer et al. (4) showed that correctly-designed scenarios as well as appropriate performance measurements were critical for proper implementation of simulations for training and research. More recently, Matas et al. (5) suggested that driving simulator validity was highly dependent on the specific population under study and the scenarios selected (see also Mullen et al. (6)).

Regarding specific driving populations, two specific age groups have principally been investigated. Studies have been done to develop reliable simulator-based driving assessments for older drivers (7–9). Driving simulators have also been used to develop the best means of helping young drivers attain automaticity in their basic vehicle control skills (10). Despite driving less on average, elderly drivers are known to be involved in more lethal crashes and have more traffic convictions as compared to any other adult age group (11–13). Furthermore, young drivers are known to be involved in the greatest amount of accidents as compared with any other age group (14). This makes sense considering their relative inexperience as well as their propensity to take greater risks while driving (15). Exact reasons notwithstanding, the observed crashes among younger and older drivers cannot be attributed to the same root causes but both may be linked, in part, to difficulties in managing driving situations under high cognitive workload (16). What is not well understood, however, is how age differences manifest due to variations in mental workload.

When attempting to conceptualize human driving behavior, Keskinen (17) proposed a four-level, hierarchical model to explain the interplay between different elements of driving skills across levels (see also Hatakka et al. (10)). The importance of the two higher levels that concern social and personality traits (*i.e.* "goals for life and skills for living" and "goals and context of driving") is not obvious in the context of virtual reality. However, driving simulators seem to be ideal tools for assessing the relationship between the two lower levels (*i.e.* "mastering traffic situations" and "vehicle maneuvering"). Until recently, most driving simulator studies focused on single measures of "vehicle maneuvering" such as mean driving speed, direction and lane position (18). Following the increased awareness that single measures, *e.g.* mean driving speed, are insufficient criteria to evaluate risky driving behavior (19), there has been renewed interest in the "mastering traffic situations" level. In line with this idea, some studies investigated the link between functional (*e.g.* cognitive abilities such as attention) and driving measures (*e.g.* mean speed) to assess the potential influence of "mastering traffic situations" on "vehicle maneuvering" level (20–23). The striking correlations between cognitive ability and driving measures found in these studies reinforce the idea that vehicle driving in traffic is a complex task involving multiple cognitive and perceptual processes such as attention, working memory and executive functioning (24). These relationships are further demonstrated by a growing body of literature on the aging process that demonstrate that decrements in perceptual and cognitive abilities may be associated with decreased driving performance in healthy, aged drivers (25, 3, 26).

Studies of the aging process and driving also investigated to what extent specific cognitive functions predict driving ability. In such paradigms, cognitive functions were assessed through multiple neuropsychological tests and driving measures were recorded throughout a single drive, in predefined and similar conditions. Nevertheless, it is well known that human performance is also dependent on the task demands or mental workload, within each ecological context (27). Individuals have a limited cognitive capacity (28). When resource demands exceed resource availability, performance can be impaired (27). Mental workload increases with driving complexity (29,30). Therefore, when considering the context of a driving study, scenarios need to be designed with an appropriate level of difficulty and mental workload to identify subtle differences in driving behavior. For example, a driving scenario that is not sufficiently challenging might not detect differences in driving performance measures. Conversely, driving scenarios that are too difficult or that present unrealistic driving events might create excessively high mental loads that do not reflect natural driving behavior. To date, few studies have investigated the scenario characteristics that affect mental workload during driving. Steyvers & De Waard (31) and Cnossen et al. (32) investigated the influence of roadway characteristics and driving speed, respectively, on subjective as well as physiological measures of mental workload. These studies show that increasing task complexity affects mental workload and can negatively influence driving ability. We are unaware of any attempts to analyze and classify the driving conditions associated with mental workloads appropriate for the dual purposes of eliciting realistic behavior in challenging circumstances and making valid inter-individual comparisons of driving behavior. For instance, despite evidence that older drivers compensate for age-related increases in response time by adopting slower speeds (2), the basic question about whether an individual's driving speed should be tightly controlled in cross-sectional research remains unanswered.

In the present experiment, we assessed the influence of mental workload on driving measures between different age groups by manipulating the situation complexity in distinct simulator scenarios, each one representing a different driving environment with a different mental workload. Additionally, we used a psychophysical task known as 3-Dimensional Multiple Object Tracking (3D-MOT) to link an individual's ability to capture and integrate relevant information in a highly complex visual environment (33, 34) to measures of driving performance (35) under different mental workloads.

Material and methods

Participants

A total of 115 licensed drivers between the ages of 18 and 86 (mean = 50.28 ± 25.52 (SD) years old) were recruited from the Université de Montréal's School of Optometry during routine visits or else were referred by the Québec driving license and public auto insurance authority, the SAAQ (Société de l'Assurance Automobile du Québec). All participants were healthy and reported normal or corrected-to-normal vision (*i.e.* visual acuity score of 6/7.5 or better with both eyes in Snellen chart and stereoscopic acuity of 50 seconds of arc or better in Randot test). Participants were free of visual, neurological, musculoskeletal, cardiovascular and vestibular impairments. The study adhered to the tenets of the Declaration of Helsinki (last modified, 2004), all tests and procedures were approved by the ethics committee of the Université de Montréal [Comité d'éthique de la recherché en santé (CERES); certificate N˚ 11-082-CERSS-D] and all volunteers signed forms indicating informed consent. To capture a wide range of driving behaviors, volunteers were separated into three different groups based on their age and level of driving experience. The first group was composed of twenty-nine young adults, inexperienced drivers (< 1 year of experience driving) ranging in age from 18 to 21 years of age (mean = 20.15 ± 1.19). The second was a group of thirty-five experienced (≥ 5 years of experience driving) adults ranging from 25 to 55 years of age (mean = 36 ± 8.68). Finally, the third group consisted of fifty-one experienced (≥ 40 years of experience driving) older drivers ranging from 70 to 86 years of age (mean = 77.20 ± 5.01).

Apparatus

A VS500M car driving simulator (Virage Simulation Inc.®) was employed for all driving sessions. This high fidelity, motion-based driving simulator uses real car parts for the cockpit that includes a real car seat, steering wheel, controls, indicators, dashboard and pedals. The steering wheel provides realistic force feedback and the accelerator and brake pedals function as in a typical car. The computerized driving simulation task was displayed under ambient lighting on three 50-inch plasma screens with 1280 x 720-pixel resolution allowing a full 180° field of view. Two additional smaller screens are placed beside and behind the participants to replicate the blind spot areas of the car. Rearview and side mirrors were inset in the central screen to approximate their spatial positions in a real car. The simulation was made even more immersive with motion and sound cues. Realism is enhanced by haptic feedback from a motion system consisting of a compact three-axis platform with electrical actuators that provide acceleration, engine vibration and road texture cues as a function of driving speed. A stereo sound system provides naturalistic engine and external road sounds and the Doppler Effect to recreate the sounds of passing traffic, also as a function of driving speed.

Scenario design

While reviewing the relationship between mental workload and driving, Paxion et al. (36) summarized the taxonomy of situation complexity (see also [18, 37]) as depending on the "road design (*i.e.* motorways vs. rural roads vs. city roads), road layout (straight vs. with curves, level vs. inclined, junction vs. no junction) and traffic flow (high density vs. low density)". Following this, the urban scenario was designed to invoke the sensation of driving in the downtown core of a populated city center and thus involved many more intersections, turns and traffic than the other scenarios. The highway scenario, by comparison, involved fewer of these elements. It was designed to be low in mental loading due to the scarcity of turns, intersections and distracting visual information. Finally, the rural scenario was designed as a middle ground between these two scenarios. The road design, visual information and traffic flows used in these three scenarios led to the following classification from high to low mental workload: urban, rural, and highway.

Protocol

Participants were tested in two experimental sessions separated from each other by a week. Each session lasted approximately one hour. The first session consisted of a visual exam including ETDRS (Early Treatment Diabetic Retinopathy Study) visual acuity testing, Humphrey visual field testing as well as Randot stereoacuity tests meant to screen any drivers with obvious uncorrected visual deficits. The Mini-Mental State Exam (MMSE; Folstein et al. (38)) was also included to screen individuals with strong cognitive impairment. Finally, participants were invited to try the driving simulator in an unrecorded session lasting twelve minutes (two scenarios of six minutes each). This initial introduction to the driving simulator was intended to allow participants to adapt to the simulated environment reducing potentially confounding factors such as Simulator Adaptation Sickness or unfamiliarity with handling the simulator vehicle during the actual testing session (39).

The second session included the assessment of subjects' perceptual-cognitive skills with a 3-dimensional multiple object-tracking task (the 3D-MOT) adapted from Pylyshyn & Storm (33). We implemented this test using a technology known as the NeuroTracker^{TM} (CogniSens) to assess the speed at which our participants could simultaneously track and attend multiple moving objects (34). Next, participants were tested on the three distinct simulator scenarios, each representing different driving environments with different mental workload. Importantly, in each scenario, participants were instructed to drive as they normally would and follow visual and oral navigational instructions while respecting road signage, other road users and posted speed limits (*i.e.* 50 km/h in urban, 70, 90 km/h in rural and 100 km/h in highway scenario). In addition, to elicit their natural driving speed selections, no instructions were given about maintaining minimal speeds. Each of the three scenarios contained five to seven different skill testing, often dangerous, events that forced participants to respond (see Figure 1) and that were triggered at pre-programmed moments along the route. These events were homogenized across the three scenarios following the typology presented by Borowsky & Oron-Gilad (40) in their study on hazard perception. Each scenario incorporated both single-phased (i.e. hazard is always visible) and two-phased materialized hazards (i.e. hazard is hidden before becoming visible) that were either other vehicles or pedestrians and which required specific evasive responses and/or a sudden brake to navigate through safely. Participants' results were averaged across all events for each scenario in order to provide large enough samples of their driving behaviour from which to conduct subsequent analyses.

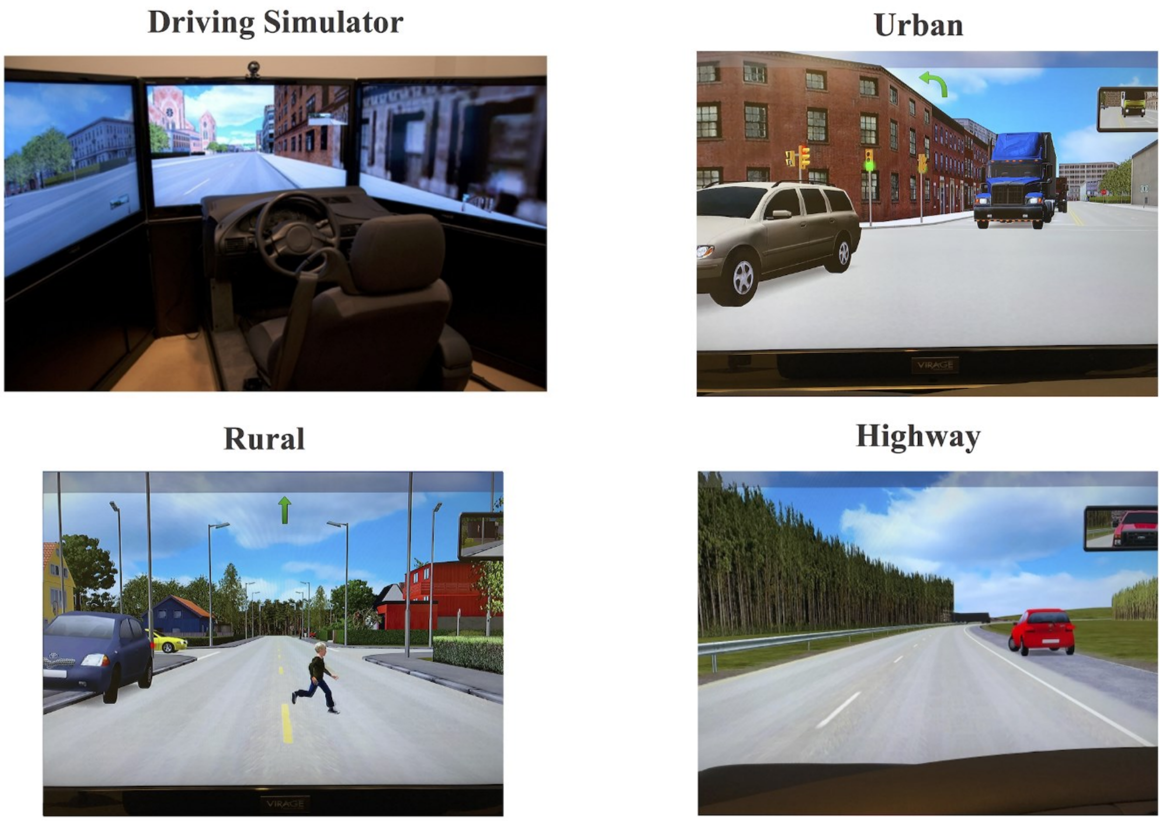

Figure 1. – Image of the VS500M driving simulator and example of events belonging to the single visible conflict category within the Urban, Rural and Highway scenario.

Driving measures

To capture subtle changes in driving behavior between the three age groups, driving performance was evaluated using 18 specific driving measures (see Table 1). Driving is an inherently multifactorial task and variations in driving ability cannot necessarily be well understood based on any single measure or combination of different measures (41). Therefore, rather than exclude potentially interesting measures based on subjective criteria, we developed a methodology aimed at better capturing the nuanced driving behavior of our subjects while also reducing our dataset to the most pertinent measures. Thus, all the measures recorded by the driving simulator were initially involved in our analyses. As a preliminary step, we performed a bivariate correlation on these 18 measures aggregated across the three scenarios. Based on this analysis, we controlled for the influence from varying mean driving speed and excluded variables correlated with this measure from further analyses. This preliminary step allowed us to exclude redundant and irrelevant information based on objective criteria.

Four of the 18 selected measures have been widely used in driving simulator studies: “Crash”; “Near crash”; “Mean speed” that reflects a compensation strategy for age-related increases in response time (2) and standard deviation of lateral position (“SDLP”), which has been shown to be a sensitive measure of driver impairment (16, 42).

The remaining 14 measures are found less often in the literature but were selected for their potential to provide useful information. Notably, measures relying on the abrupt or unnecessary actions taken on the vehicle such as “Max brake”, “Distance at max brake”, “Max steer change rate”, “Distance at max steer change rate” and “Steer range” (see Table 1 for a further description) might reveal poorly adapted and thus potentially risky behavior. Additionally, some of the measures reflect different responses adopted while facing hazardous events. The following are examples of measures that were taken during each event of interest: the distance and mean speed at which the gas pedal was released (“Gas release speed” and “Gas release distance”); the distance and mean speed at which brake pedal was pressed (“Brake speed” and “Brake distance”), and: the instant that the vehicle started decelerating for a minimum of three seconds (“Speed at anticipation” and “Anticipation distance”). The above listed measures were triggered at “event onset”, which is defined by a pre-programmed trigger occurring when a conflicting object enters the driver’s cone of vision (an invisible ‘cone’ traced in front of the vehicle that represents the visual information available to the forward-facing driver). Events were considered complete after the driver had proceeded through the scene and the object of interest was outside the cone of vision, regardless of participants’ reactions or event outcome. Apart from Mean speed and SDLP (which were computed along the entire scenario), the other 16 measures corresponded to the mean of values recorded on each event belonging to the same scenario.

Table 1. – Definition of the studied measures and their units.

	Measure	Unit	Description
1	**Crash**	n	Whether a collision occurred or not during the event.
2	**Near crash**	n	When within an event: - Subject brakes harder than a given threshold (0.7 for the rural scenario, 0.75 for other scenarios) while driving at a speed greater than 5 m/s (18km/h) - The steering wheel is turned more than 60 degrees while driving faster than a speed threshold (5 m/s) - The participant drives within 3 m of an object while travelling at a speed greater than 10m/s (36km/h) for the rural scenario, 5 m/s for other scenarios)
3	**Mean speed**	km/h	Average speed of all driving. For each data point, speed inferior to 10 km/h or recorded 300 m before and 100 m after an event were discarded from the averaging.
4	**SDLP**	m	Standard deviation of lateral position. Same exclusion criteria as mean driving speed computation were used. Additionally, for each data point, lateral position recorded 10 seconds before and after a lane changing were discarded from the averaging.
5	**Max brake**	n	Hardest amount of braking applied during event of interest. Where 0 = no braking applied, 1 = pedal is fully depressed.
6	**Distance at max brake**	m	Distance from object at which "Max brake" is recorded
7	**Max steer change rate**	degrees / s	Most extreme (in terms of range and speed) left or right steering wheel position change during event of interest.
8	**Distance at max steer change rate**	m	Distance for the most extreme (in terms of range and speed) left or right steering wheel position change during event of interest
9	**Steer range**	degrees	Difference in degrees between leftmost and rightmost steering wheel position for event of interest.
10	**Closest distance**	m	Minimum distance between participants' vehicle and object during event
11	**Speed at closest**	m/s	Speed at which car is travelling when at minimum distance between participant and object during event.
12	**Hazard rating**	log	Log of "Speed at closest" divided by the minimum distance between the participant's vehicle and the

		(m/s/m)	object. If there is a crash, this is computed from the last data point prior to the crash.
13	**Gas release speed**	m/s	Speed of vehicle at point when gas pedal is released for event of interest.
14	**Gas release distance**	m	Distance from object during event of interest when gas pedal is released.
15	**Brake speed**	m/s	Speed at which brake pedal is pressed during event of interest.
16	**Brake distance**	m	Distance from object at which brake pedal is pressed during event of interest.
17	**Speed at anticipation**	m/s	Speed at which vehicle starts decelerating for a minimum of 3 seconds for event of interest.
18	**Anticipation distance**	m	Distance from object at which vehicle starts decelerating for a minimum of 3 seconds for event of interest.

n corresponds to an undefined unity, m to meters, s to seconds, km to kilometers, h to hours and log to logarithm.

Statistical analysis

Initially, bivariate correlations using the Pearson method were used to assess the relationship between the 18 driving measures aggregated across the three scenarios. A preliminary check of our data revealed that some variables violated the assumption of normality. Thus, non-parametric Spearman correlations were conducted for these variables.

Secondly, bivariate correlations were conducted on a scenario-by-scenario basis for variables that did not correlate with mean driving speed in our previous analysis. Partial correlations controlling for mean speed were employed to account for our decision to allow participants full control over their driving speed. Additionally, to investigate the differences in driving performance between age groups, Analyses of Covariance (ANCOVAs) controlling for mean speed was also conducted with these measures for each scenario. Parametric ANOVA was conducted on any dependent variables that did not significantly correlate with the covariate, (*i.e.,* 'mean driving speed'). In each case, post-hoc comparisons using Tukey's HSD test were performed to explore differences between age groups. Non-parametric bootstrap-based ANOVA was performed on the variables that were non-normally distributed (number of iterations = 1000). This robust statistical method maintains the Type I error rate of the tests at its nominal level while also maintaining the power of the tests, even when the data are heteroscedastic and do not show normal distributions (43, 44). In this specific case, multiple pairwise comparison procedures using the bias-adjusted percentile bootstrap method (45) were performed to explore differences between age groups.

Finally, to investigate how the scores obtained in the perceptual-cognitive task predict driving performance in relation to mental workload levels, we performed bivariate correlations between the scores obtained in the 3D-MOT task and the driving measures. 3D-MOT scores were measured using mean speed thresholds as the dependent variable and were computed based on the last four reversals of a 1-up 1-down staircase procedure with thirty trials. Correct or incorrect responses on each trial resulted in a proportional speed increase or decrease of 0.05 log units, respectively. Given the distribution of such psychophysical data, a logarithmic transformation was applied to the scores to permit conducting bivariate correlations between those scores and the driving measures. It has been suggested that multiple object tracking is a task correlated with some measures of driving ability (35, 46). Therefore, it is conceivable that 3D-MOT might be a better predictor of risky driving behaviour than age and naturally adopted mean driving speed. Thus, for each driving measure we performed multiple linear regression analyses with Age, 3D-MOT score and mean driving speed as predictors.

Results

Mean driving speed and relevance of the driving measures

Pearson or Spearman correlation coefficients were computed between each driving measure. All the correlations were computed on values aggregated across the three scenarios and are summarized in Figure 2.

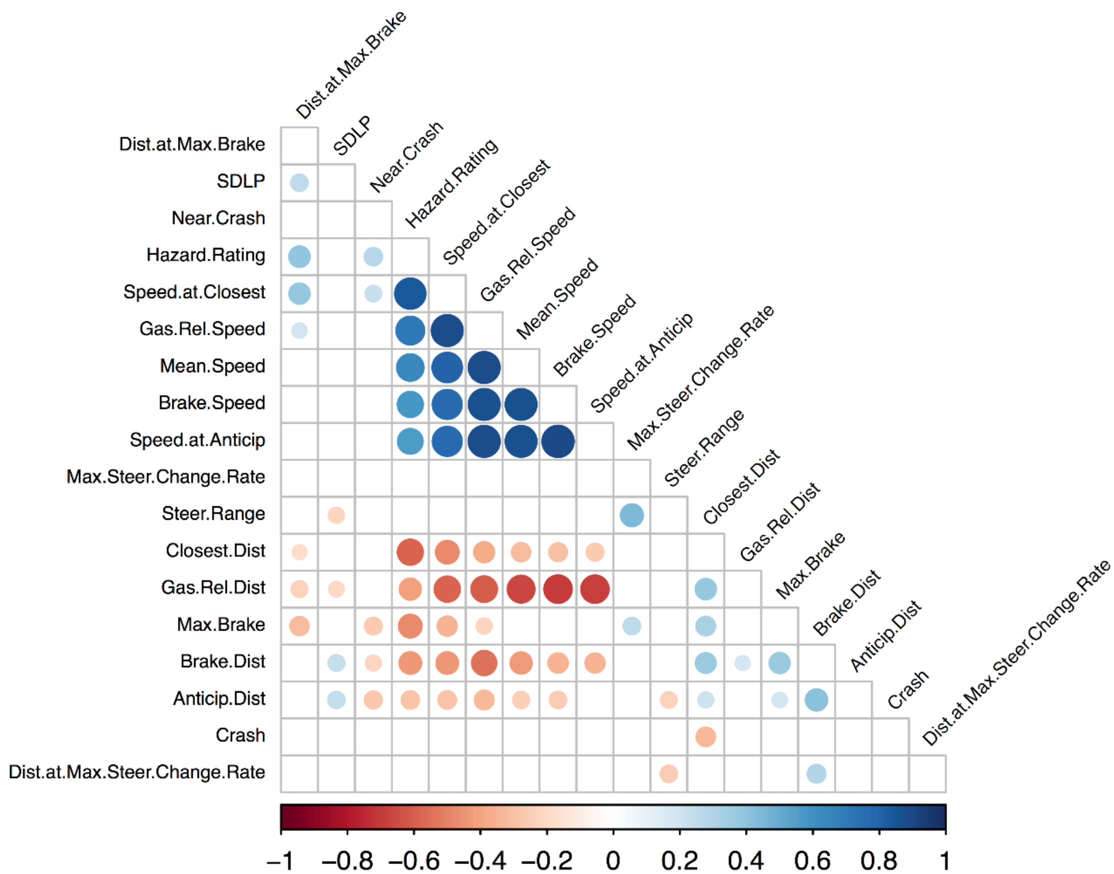

Figure 2. – Graphical representation of the correlational analysis on the aggregated dataset performed using hierarchical clustering analysis in the R statistical environment (R Development Core Team, 2008).

As expected, variables taking participants' speed into account were very strongly correlated with mean driving speed. A hierarchical clustering analysis identified two clusters of variables: one centered around mean speed and including positive correlations, and the other with negative correlations between speed measures and distance measures (Figure 2). These latter relationships indicate that the higher the mean driving speed, the smaller the distances at which participants made their decisions regarding the event of interest. Thus, all these variables can be considered redundant and excluded from further analyses as they offer no additional/substantial information beyond the mean speed. Other measures such as Crash, Near crash, Standard deviation of lateral position (SDLP), Max steer change rate, Distance at max steer change rate, Max brake, Distance at max brake and Steer range were found to be independent of excessive mean speed influence and, as such, may provide relevant information for by-scenario analyses.

Influence of mental workload on driving measures

Urban scenario

We employed three scenarios of varying difficulty to determine which mental workload was the most appropriate to highlight subtle differences in driving behavior between drivers varying in experience. We first examined driving performances across age groups in the Urban scenario (designed to provide high challenge and thus high mental workload). Interestingly, correlations performed on measures recorded during this scenario showed that age was positively correlated with Max brake ($r(115)= .33$; $p= <.001$) and negatively correlated with Steer range ($r(115)= - .3$; $p= <.001$) and Near crash ($r(115)= -.22$; $p= .019$; see Figure 3). These correlations are corroborated by the ANCOVA which revealed significant age effects for Max brake ($F(2,112)= 3.93$; $p = .02$) and Steer range ($F(2,111)= 4.36$; $p = .02$) as well as a trend for Near crash ($F(2,111)= 2.07$; $p = 0.06$; Table 2). Multiple pairwise comparisons revealed that only the oldest group differed significantly on these measures compared to both inexperienced (Max brake: $p= .06$; Steer range: $p= .03$; Near crash $p= .02$) and experienced younger adults (Max brake = $p= .05$; Steer range $p= .03$; Near crash $p= .03$). There was no significant difference for these measures between the inexperienced and experienced groups (Max brake: $p= .99$; Steer range: $p= .88$; Near crash $p= .61$).

The above-mentioned results suggest that younger participants were more likely to experience near crashes than older participants. Statistical analyses also revealed that inexperienced (mean= 40.05; SD= ± 5.89) and experienced young drivers (37.26 ± 4.86) drove faster than older drivers (30.22 ± 4.86; both p = <.001). Although the statistical analyses were designed to control for mean driving speed, the slower driving speed exhibited by older participants is well-documented (2) and might explain the trend toward an association between younger age and higher near crash risk. Inexperienced drivers also tended to drive faster compared to experienced drivers (p= .08) in this scenario (Table 2). This tendency is consistent with previous findings showing that inexperienced drivers tend to take more risks while driving (15) and that higher speeds are associated with increased crash risk (47).

A possible interpretation of the positive correlation between age and Max brake might be that older participants were more likely to make abrupt stops. Additionally, it is possible that younger drivers may put themselves at greater risk for crashes by not braking hard enough during critical events. However, this latter result coupled with the negative correlation between Max brake and Crash (r(115)= -.18; p= .049) and the non-significant correlation between Age and Crash (r(115)= -.08; p= .39) suggests that younger participants may have adopted a smoother driving style than older participants without putting themselves at greater risk. The negative correlation between age and Steer range and the age effect on Steer range in the ANCOVA also suggests that older participants made fewer steering movements than younger participants during events of interest. Together, these results suggest two different types of avoidance strategies as a function of age younger drivers tended to favor steering movements to avoid crashes and older drivers were more likely to use abrupt braking strategies.

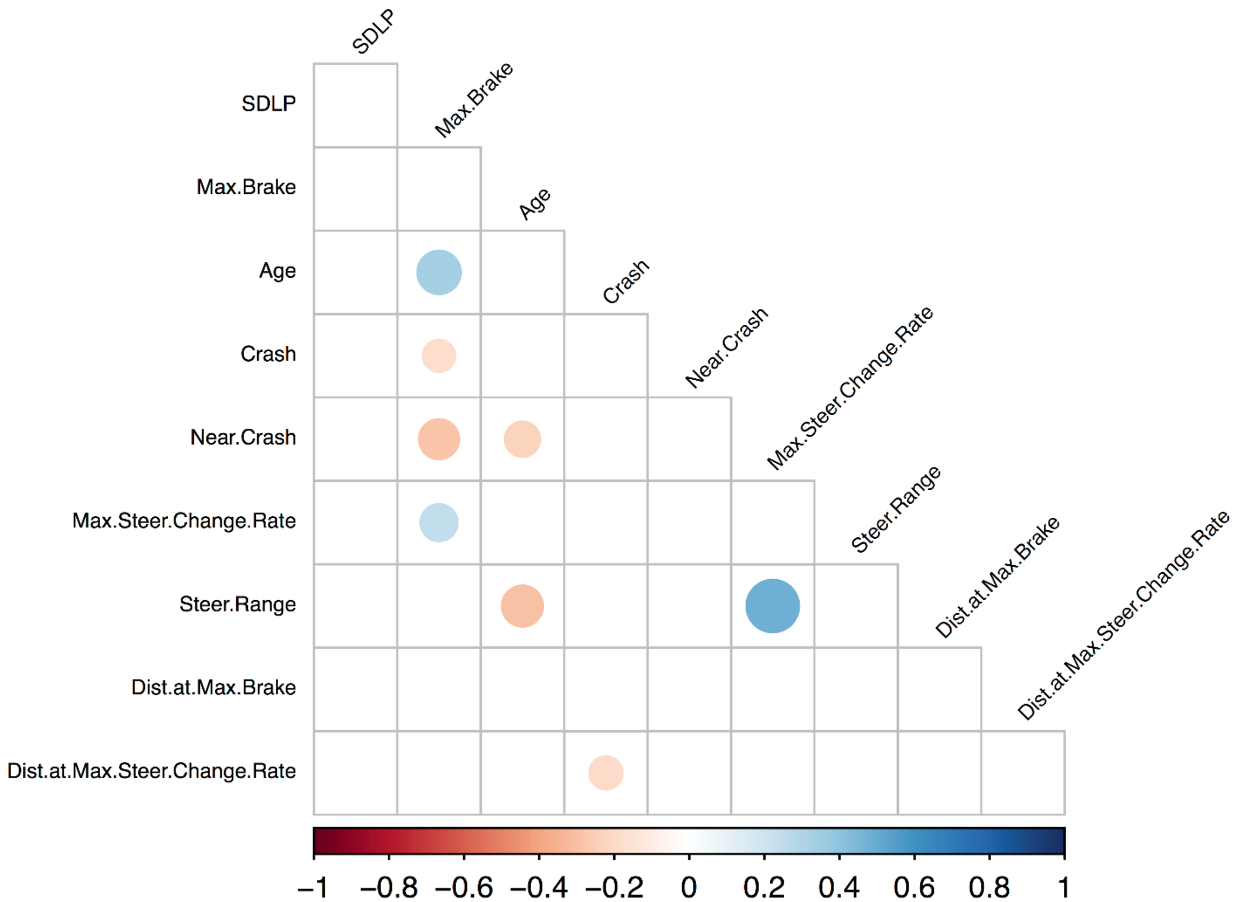

Figure 3. – Graphical representation of the hcluster correlation analysis on the 'Urban Scenario' dataset controlling for mean speed.

Table 2. – Statistical age groups comparisons between the three age groups.

Measure	**Correlated With Mean Speed**	**Main Effect**	**Inexp. vs. Exp.**	**Inexp vs. Old**	**Exp. vs. Old**
Crash	.096	.19	.25	.54	.17
Near Crash	< .001	.06	.61	**.02**	**.03**
SDLP	.32	.68	.94	.89	.66
Max Brake	.65	**.02**	.99	.06 (<)	.05 (<)

Dist. at Max Brake	.48	.89	.97	.89	.96
Max Steer Change Rate	.005	.26	.49	.94	.29
Dist. at Max Steer Change Rate	.002	.09	.54	.08	.32
Steer Range	.001	**.02**	.88	**.03 (>)**	**.03 (>)**
Mean Speed	x	**< .001**	.08	**.001 (>)**	**.001 (>)**

When mean speed was correlated with the driving measure considered, an ANCOVA controlling for mean speed was used. When mean speed appeared to be uncorrelated with the driving measure considered, a parametric ANOVA was used. For non-normally distributed driving measures bootstrap-based ANOVA were used. The p-values resulting from the pairwise comparisons between Inexperienced, Experienced and Older drivers are shown on the three most right columns. For comparisons showing a significant difference or a strong tendency, an arrow indicates the direction of the difference.

Highway scenario

Contrary to the previous scenario, the 'Highway' route was designed to create a low mental workload. Strikingly, statistical analyses revealed that only two measures were dependent on age in this scenario. Indeed, we observed a positive correlation between age and Max brake ($r(115)= .36$; $p < .001$; Figure 4) as well as a significant age effect for Max brake ($F(2,111)= 7.74$; $p <.001$) and Mean speed ($F(2,112)= 32.84$; $p < .001$; Table 3). Multiple pairwise comparisons showed the same trend regarding the age effect on mean speed as the Urban scenario: Inexperienced (mean= 83.07 km/h; SD= ± 5.49) as well as experienced young drivers (77.93 ± 10.97) drove significantly faster than older drivers did (64.33 ± 12.69; all $p < .001$). An identical pattern emerged for Max brake, with the oldest participants also being far more likely to make full stops compared to both inexperienced ($p = .003$) and experienced young participants ($p = .002$). Slower speeds observed among older participants are unlikely to be related to the difficulty of this scenario, given that it was designed to be low in complexity. Instead, it is more likely that—in the absence of any external pressure to drive more quickly—older participants simply selected to drive at slower speeds than younger participants (48). It can also be noted that despite the non-significant main effect of Age on Near crash [$F(2,112)= 1.55$; $p= .19$), multiple pairwise comparisons suggested that inexperienced drivers tended to incur more near crashes than experienced ($p= .07$) and older drivers ($p= .06$) in this scenario. This tendency might be linked to the well-documented propensity of young and inexperienced drivers to make riskier driving maneuvers (49, 50).

Rather than evidencing known age effects on measures such as SDLP [$F(2,112)= 2.42$; $p= .09$] and Crash [$F(2,112)= 1.48$; $p= .25$] (51), the present statistical analyses indicate that Steer range was a particularly interesting parameter in this scenario. Indeed, this measure was positively correlated with Crash ($r(115)= .47$; $p < .001$), Max brake ($r(115)= .29$; $p= .002$) and Max steer change rate ($r(115)= .33$; $p < .001$), and negatively correlated with SDLP ($r(115)= -.28$; $p= .003$), Distance at max brake ($r(115)= -.45$; $p < .001$) and Distance at max steer change rate ($r(115)= -.38$; $p < .001$). The pattern suggests that Distance at max steer change rate might be an important parameter to consider in this scenario. The correlation between Steer range and Max steer change rate as well as Max brake indicates compensatory actions by drivers facing risky situations, as outlined by Pacaux-Lemoine et al. (52). The negative correlations between Steer range and both Distance at max steer change rate as well as Distance at max brake further reflect these compensatory actions. More revealing, however, is the negative correlation between ‘Steer range’ and ‘SDLP’. While both measures seem intuitively related, it is important to consider that ‘Steer range’ is a measure of the absolute difference between the leftmost and rightmost steering wheel position and SDLP is related to variability in lane position. One might expect a positive correlation between these measures if variability in SDLP scores was merely related to variability introduced by one instance of extreme steering wheel action taken at the last second before a crash. Instead, the negative relationship points to greater lane position variability in individuals who did not eventually make extreme steering adjustments and thus exhibited greater vehicle control and were presumably at lower crash risk. This result is somewhat inconsistent with the body of literature suggesting that higher SDLP is associated with decreased vehicular control (53).

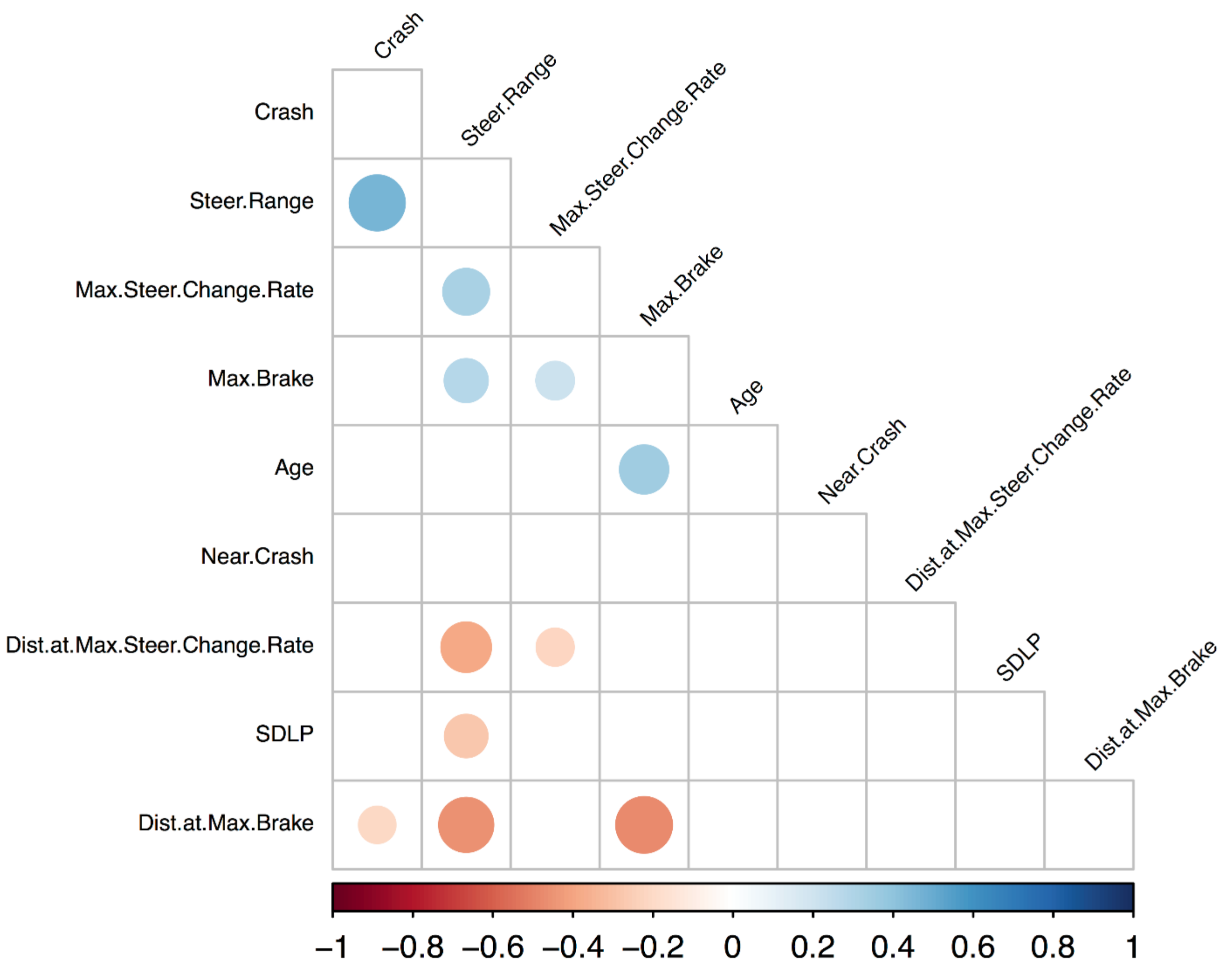

Figure 4. – Graphical representation of the hcluster correlation analysis computed in R on the 'Highway scenario' dataset controlling for mean speed.

Table 3. – Statistical age groups comparisons between the three age groups during the Highway scenario

Measure	**Correlated With Mean Speed**	**Main Effect**	**Inexp. vs. Exp.**	**Inexp vs. Old**	**Exp. vs. Old**
Crash	.66	.25	.51	.5	.16
Near Crash	.17	.19	.07	.06	.96
SDLP	.053	.09	.09	.21	.97
Max Brake	.01	**< .001**	.96	**.003 (<)**	**.002 (<)**
Dist. at Max Brake	.007	.31	.93	.57	.28
Max Steer Change Rate	.04	.1	.98	.24	.1
Dist. at Max Steer Change Rate	.09	.07	.49	.06	.49
Steer Range	< .001	.39	.67	.92	.39
Mean Speed	x	**< .001**	.14	**.001 (>)**	**.001 (>)**

When mean speed was correlated with the driving measure considered, an ANCOVA controlling for mean speed was used. When mean speed appeared to be uncorrelated with the driving measure considered, an ANOVA was used. For non-normally distributed driving measures bootstrap-based ANOVA were used. The p-values resulting from the pairwise comparisons between Inexperienced, Experienced and Older drivers are shown on the three most right columns. For comparisons showing a significant difference or a strong tendency, an arrow indicates the direction of the difference.

Rural scenario

The last of the three scenarios, the Rural scenario, was designed to produce a moderate mental workload. Contrary to the other two scenarios, here 'Age' was the measure most strongly correlated with various driving measures. Indeed, partial correlations (Figure 5) showed a positive correlation between 'Age' and 'Crash' ($r(115)= .21$; $p= .025$), 'SDLP' ($r(115)= .29$; p

=.002), ‘Max steer change rate’ (r(115)= .22; p= .019), ‘Distance at max steer change rate’ (r(115)= .22; p= .02), ‘Distance at max brake’ (r(115)= .19; p= .04) as well as a strong tendency for the correlation between ‘Age’ and ‘Max brake’ (r(115)= .18; p= .056). Statistical comparisons between the three age groups (Table 4) corroborate some of these interrelationships by showing that Age was a determinant factor for crash occurrence [F(1,112) = 3.55; p= .03] and SDLP [F(1,112) = 4.86; p= .009]. The propensity of older adults to be more involved in crashes and to show larger SDLP under increased cognitive load has been previously demonstrated (54) and linked to age-related deficits in certain driving skills (55-57). Nevertheless, the important result here is that the rural scenario was the only one to reveal these age differences, suggesting that the mental workload involved in this scenario might be the most efficient method for detecting subtle age differences.

Interestingly, multiple pairwise comparisons showed that older drivers were significantly more likely to have a crash on this route compared to both inexperienced (p= .047) and experienced drivers (p= .008). The breakdown of the main age effect of ‘SDLP’ revealed that older drivers showed significantly greater SDLP than inexperienced drivers (p= .008) but there was no significant difference with experienced drivers (p= .17). The same pattern of results was observed in ‘Distance at max steer change rate’. While the one-way ANOVA showed a significant age effect [F(1,112) = 4.03 p= .02], multiple pairwise comparisons demonstrate that this effect was mainly attributable to the significant difference between older and inexperienced drivers (p= .02). There was no significant difference between older and experienced drivers (p= .82) nor between inexperienced and experiences drivers (p= .1). The lack of significant differences in driving behaviors between inexperienced and experienced drivers might reflect the fact that even relatively inexperienced drivers are capable of quickly learning basic vehicle maneuvering and traffic situations while still lacking the higher-order skills and motivations necessary to be safe in the wide variety of contexts seen in real-world driving (see Hatakka et. al. (10) for a review). Thus, the performance deficit observed in older drivers is also unlikely to be related to basic driving skills and may reflect greater sensitivity to increased task demands. Ultimately, these results reinforce the idea that performance on the rural scenario might be the most sensitive to subtle differences in driving behaviors.

Finally, while one-way ANOVA again revealed a significant age effect on the mean driving speed on this scenario ($F(2, 112) = 10.01$, $p < .001$), the quantitative differences in mean speeds of the three groups (inexperienced: 73.81 ± 6.6; experienced: 72.21 ± 7.24; older: 65.45 ± 11.04) actually represent smaller percent differences (12% between the slowest and fastest groups) compared to the Urban (28%) and Highway (25.43%) scenarios. The relative equalization of mean speed observed may thus position the moderate complexity Rural scenario as a particularly valid representation of naturalistic group differences in behavior when faced with hazardous driving events.

Taken together, these findings suggest that after perceiving potential threats, older drivers took defensive measures earlier than younger drivers but were also less likely to identify these threats in sufficient time to react appropriately. This pattern might be related to slowed and altered motor responses among older individuals (58, 59) but may also be linked to perceptual-cognitive changes (7, 60) associated with ageing. While the nature of such changes has been studied extensively, researchers have only recently explored their implications for driving safety (35, 44).

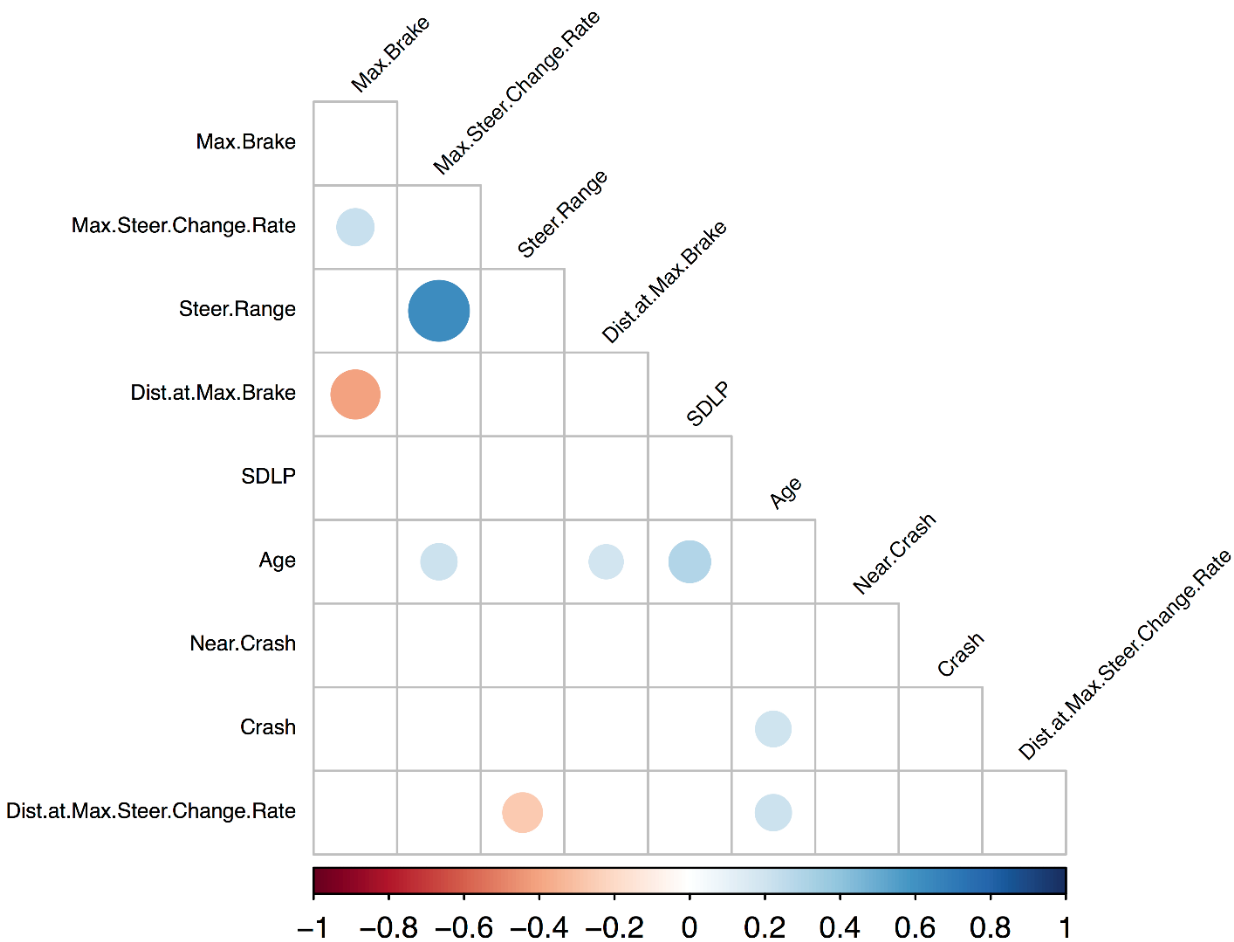

Figure 5. – Graphical representation of the hcluster correlation analysis computed in R on the 'Rural Scenario' dataset controlling for mean speed.

Table 4. – Statistical comparison between the three age groups during the Rural scenario.

Measure	**Correlated With Mean Speed**	**Main Effect**	**Inexp. vs. Exp.**	**Inexp vs. Old**	**Exp. vs. Old**
Crash	.08	**.03**	.49	**.047 (<)**	**.008 (<)**
Near Crash	.63	.32	.27	.98	.25

SDLP	.93	**.009**	.42	**.008 (<)**	.17
Max Brake	.71	.06	.77	.33	.06
Dist. at Max Brake	.07	.49	.92	.78	.47
Max Steer Change Rate	.49	.16	.96	.21	.29
Dist. at Max Steer Change Rate	.42	**.02**	.1	**.02 (<)**	.82
Steer Range	.03	.71	.99	.8	.73
Mean Speed	x	**< .001**	.76	**.001 (>)**	**.003 (>)**

When mean speed was correlated with the driving measure considered, an ANCOVA controlling for mean speed was used. When mean speed appeared to be uncorrelated with the driving measure considered, an ANOVA was used. For non-normally distributed driving measures bootstrap-based ANOVA were used. The p-values resulting from the pairwise comparisons between Unexperienced, Experienced and Older drivers are shown on the three most right columns. For comparisons evidencing a significant difference, an arrow indicates the direction of the difference.

Perceptual-cognitive measures

The use of different scenarios reveals several subtle differences in the driving performance of our three age and experience groups. Critically, the identification of these differences seems to require driving scenarios with appropriate levels of difficulty and mental workload (i.e. the Rural scenario). The main age difference was observed in the control of vehicle speed with older participants driving more slowly than younger ones. Nevertheless, current driving measures are not sufficient to explain these large differences in mean speed. Additionally, except for the mean speed measure, age differences were not indicative of other changes in vehicle control measures. Instead, differences may reflect how older individuals process and respond to upcoming events.

To investigate this idea, we turned to the NeuroTracker measures and examined bivariate correlations between 3D-MOT scores and driving measures recorded during the Rural scenario (i.e. the scenario showing the greatest age differences). Strikingly, statistical analysis revealed that 3D-MOT scores were significantly correlated with 'Crash' ($r^2(113) = -.31$, $p < .001$), 'SDLP' ($r^2(113) = -.26$, $p < .005$), Distance at Max Steer Change Rate ($r^2(113) = -.2$ $p = .03$) and Mean Speed ($r^2(113) = .47$, $p < .001$) measures (Table 5 and Figure 6). These results show that the more the perceptual-cognitive abilities were altered (as evidenced through NeuroTracker speed thresholds), the more driving speed decreased and crash occurrence increased. These findings are consistent with the hypothesis that the low mean speed observed in older people is linked to a self-restriction due to the alterations of their perceptual-cognitive abilities. A decrease in these abilities has been previously linked to crash risk (see Anstey et. al. (61) for an in-depth review). While past research has focused on more isolated perceptual-cognitive factors (i.e. selective and divided attention, processing speed, useful field of view, etc.), to date comparatively little research has made use of more integrative and dynamic tests like the NeuroTracker. If decreased perceptual-cognitive ability is indeed related to driving performance, then we should expect performance on the NeuroTracker to be associated with of our driving measures.

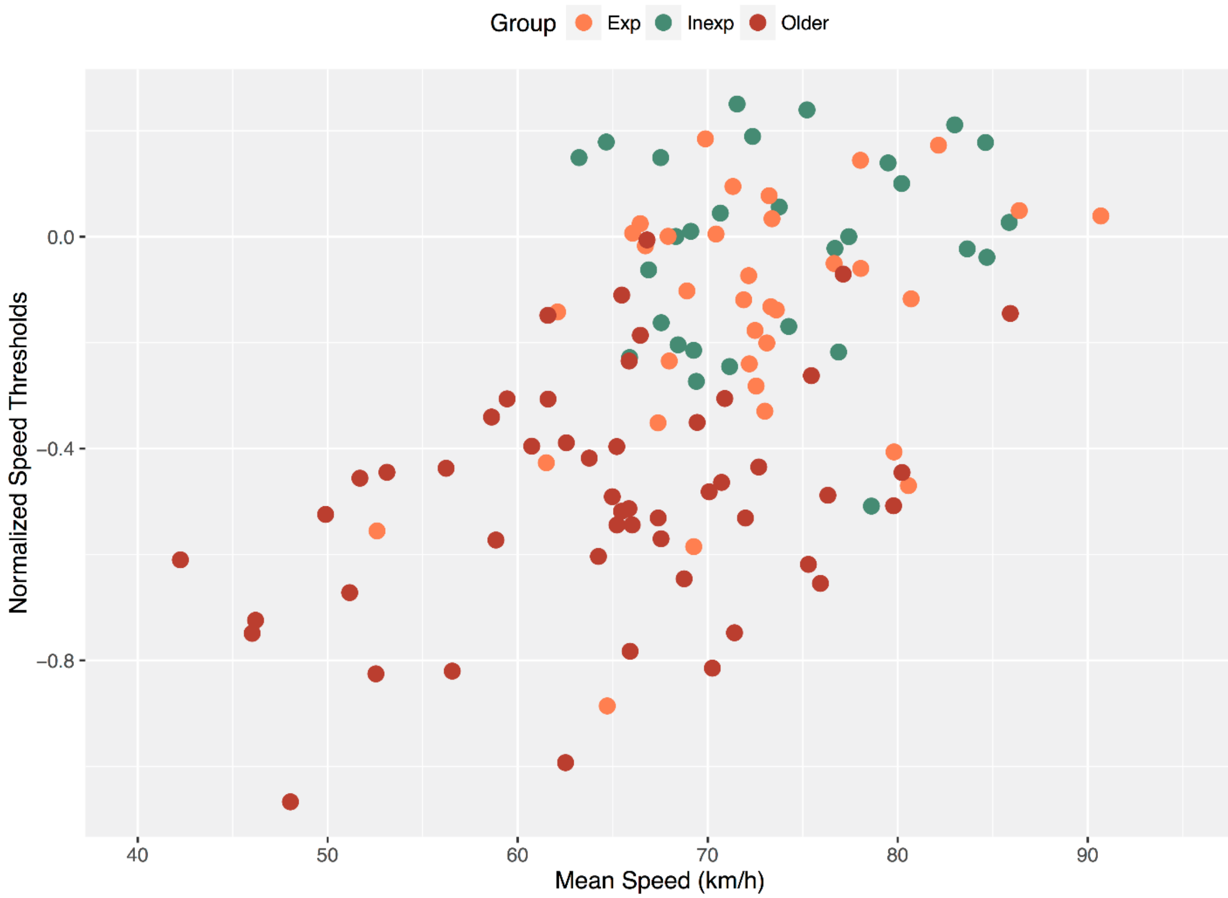

Figure 6. – Correlation between NeuroTracker speed thresholds (represented in log units) and mean speeds naturally adopted in the rural scenario.

Table 5. – The 3D-MOT as a predictor of a risky driving behavior.

***Measure* (Rural)**	R^2	***p***
Crash	-.31	**< .001**
Near Crash	-.04	.65
SDLP	-.26	**.005**
Max Brake	-.01	.92

Dist. at Max Brake	.-.07	.45
Max Steer Change Rate	-.07	.47
Dist. at Max Steer Change Rate	-.2	.03
Steer Range	.16	.09
Mean Speed	.47	**< .001**

Bivariate correlations between perceptual-cognitive measure and driving measures across the three scenarios.

We subsequently performed a multiple linear regression analysis on these data to model the extent to which these driving measures could be predicted by Neurotracker speed thresholds, age and mean driving speed. These latter two measures were included within the model as additional predictors to clarify the relative value of each component. The model significantly predicts crash [F(3,111)=4.53; p= .005; R^2= .33], SDLP [F(3,111)= 4.37; p= .006; R^2= .32], Distance at max brake [F(3,111)= 3.06; p= .03; R^2= .28] and Mean speed [F(3,111)= 16.66; p < .001; R^2= .48] and shows a tendency to predict Max brake [F(3,111)= 2.36; p= .07; R^2= .25] as well as Distance at max steer change rate [F(3,111)= 2.26; p= .09; R^2= .24]. However, this model was non-significant for the measures Near crash [F(3,111)= 1.11; p= .35; R^2= .17], Max steer change rate [F(3,111)= 2.03; p= .11; R^2= .23] and Steer range [F(3,111)= 1.84; p= .15; R^2= .22]. Interestingly, NeuroTracker speed threshold was the only significant predictor of crashes (β = -.36; t= -2.75; p= .007) and was predictive of naturally adopted mean speed (β = .37; t= 3.18; p= .002) (Table 5b). Additionally, whereas NeuroTracker speed threshold only shows a tendency to predict 'Max brake' (β = .23; t= 1.75; p= .08), age emerged as a significant predictor of 'Max brake' (β = .34; t= 2.61; p= .01). Finally, Mean speed predicted 'Distance at max brake' (β = .3; t= 2.83; p= .006). Such results are consistent with recent results from MacKenzie & Harris (35) who also demonstrated the usefulness of MOT and measures of attentional resources in predicting aspects of driving performance as well as more pronounced effects related to road complexity. Thus, our findings support the growing research consensus that age-group related differences in driving behaviors are associated with measurable changes in underlying perceptual-cognitive abilities (35, 62, 63).

Table 6. – Multiple linear regression analyses performed on measures recorded during the rural scenario.

Predictor		**Crash**	**Near Crash**	**SDLP**	**Max Brake**	**Dist. at Max Brake**	**Max Steer Chg. Rate**	**Dist.at Max Steer Chg. Rate**	**Steer Range**	**Mean Speed**
LogNT	β	-.36	-.11	-.21	.23	-.11	.02	-.1	.04	.37
	p	**.007**	.42	.12	.08	.4	.89	.47	.74	**.002**
Age	β	.02	-.17	.2	.34	.14	.25	.18	-.06	-.15
	p	.87	.2	.13	**.01**	.28	.06	.17	.63	.21
Mean Speed	β	.13	-.14	.17	-.02	.3	.16	.04	.15	x
	p	.2	.2	.11	.85	**.006**	.14	.7	.15	x

3D-MOT scores, Age and Mean driving speed were entered as predictors in the model. For each driving measure, regression weights (β) and significance value (p) are shown.

Discussion

Mental workload and driving measures

The main aim of the present study was to determine the degree to which scenario complexity produces an appropriate level of mental workload for the dual purpose of: 1. eliciting realistic behavior in challenging circumstances and 2. revealing subtle differences in driving ability across a wide-range of different age and experience groups. Numerous studies confirm the existence of differences in driving behavior both on-road and in a driving simulator between age groups and levels of experience (56, 64-67). By manipulating the situation complexity in three distinct simulator scenarios, we showed that reliably identifying said differences in cross-sectional research seems to require a scenario designed with a moderate level of difficulty and workload.

Indeed, only one scenario, the Rural, exhibited large correlations between age and well-known driving measures such as crash occurrence, a clear negative outcome, and SDLP, a sensitive measure of driver impairment (68). The limited age effect on driving measures observed in our Urban scenario (i.e. high demand) suggests that the scenario's increased mental workload and slower required driving speed may have homogenized participants' reactions and behavior enough to mask subtler differences between how different age groups respond to challenging driving events. A few differences were found in the types of potentially risky driving behavior exhibited by different age groups, i.e. in measures linked to a performance deficit such as near crashes and in the differences in danger avoidance strategies. Similar outcomes were found for the Highway (low demand) scenario.

A better understanding of the optimal mental workload for testing differences between age groups in driving simulator studies is of social interest because it has been recognized that mental workload related problems are responsible for most road accidents (69). Given that the cognitive capacity of the human brain is limited (28, 70), that aging is associated with decreased cognitive capacity (54, 71) and that task performance can be impaired when the resource demands exceed resource availability (27), one might expect a close relationship between increased age, scenario complexity and poor driving performance. Not all our results indicated an association between factors related to age and scenario complexity. Some of these agree with the models proposed by Meister (72) and de Waard (16) that assume that in cases of either extreme high or low task demands, drivers can become overloaded or under aroused and thus task measures may lose some sensitivity. Thus, the similar results observed between the high-complexity Urban scenario and the low-complexity Highway scenario might be in-part explained by decreased vigilance during the low-demand scenario resulting in a higher mental workload for the events themselves (16). A review of the literature done by Paxion et. al. (36) has made similar suggestions in this regard. This interpretation, indicating an "inverse-U" model of the mental workload effects on performance, is corroborated by our finding that the Rural scenario was best at naturally reducing age group mean speed variability—another factor worthy of discussion in the context of cross-sectional driving simulator research.

A new outlook on mean driving speed

We did not impose a minimum driving speed on participants to gain insight into their natural driving behavior. One of the main findings of the present study is the degree to which drivers of different age groups naturally self-select their driving speeds. In the absence of external pressure to drive more quickly, older adult participants drove significantly slower than both inexperienced younger and experienced adult participants. Though slower driving speeds could be expected for older drivers (2), artificially slower speeds might be problematic in the context of driving studies that seek to measure reactions to dangerous events. Indeed, slower drivers would have more time to perceive and process upcoming threats and react appropriately.

This result already provides one important insight for studies investigating potentially risky driving behavior: While naturally-adopted mean speeds are informative, individuals' driving speeds in the simulator should be somewhat controlled to better ensure that the task elicits ecological driving behavior for all participants. Moderate scenario complexity may be one method of naturally reducing mean speed variability between age groups as observed in the Rural scenario. Beyond that, other relatively unobtrusive solutions such as sensory feedback should be investigated to reduce the range of this variability without eliminating it entirely. Finally, given the well-documented decrease in visual processing speed of older adults (73), one could imagine that encouraging more equal driving speeds may further distinguish the driving performance of different age groups.

Novel measures of driving performance: uncontrolled and abrupt maneuvers

Several novel driving metrics were conceived of and evaluated to determine their usefulness in quantifying driving performance in a more nuanced fashion than traditional measures such as mean speed, crashes and 'SDLP'. Past research has suggested that driving simulator studies might be more sensitive to subtle changes in driving performance than on-road assessment (74). Thus, such studies represent an interesting opportunity to measure these subtle differences using a diverse set of driving measures. While many of these measures were ultimately excluded based on strong correlations with mean driving speed, a few did emerge as significant, non-redundant measures of driving behavior. Notably, measures of the maximum amount of force pressed on the brake pedal during events of interest ('Max brake') as well as the range and speed of steering action participants exhibited ('Max steer change rate') emerged as potential indicators of risky or useless action taken upon the vehicle. In addition, the distance at which these actions were taken ('Distance at max brake' and 'Distance at max steer change rate', respectively) seemed to identify drivers who respond later to upcoming threats and who subsequently acted in extreme ways to avoid collisions, a finding consistent with descriptions by Pacaux-Lemoine et al. (52) of drivers forced into similar simulated circumstances.

Perceptual-cognitive ability predicts driving performance

The correlations observed between NeuroTracker speed thresholds and driving measures such as crashes, SDLP and mean speed in the rural scenario reinforce the notion that the slower mean driving speed of older people may in fact reflect compensatory behavior for changes in perceptual-cognitive ability. Our multiple linear regression model demonstrated that NeuroTracker speed thresholds were better at predicting many of aspects of driving behavior than naturally-adopted mean speed and age. Numerous studies have already linked tests of perceptual-cognitive abilities with changes in driving performance due to aging (75–77). While previous studies have shown a relationship between MOT and some driving measures (35, 44), our results clearly reinforce and extend these findings to indicate that 3D-MOT is a relevant predictor of driving performances across age.

Older drivers have slower reaction times due to normal aging (78). In addition, normal aging is associated with decrements in perceptual-cognitive abilities such as visual attention (7), visual processing speed (79) and working memory (80). Many of the previously mentioned tests are designed to independently measure one of these facets of perception or cognition. While this is not inherently problematic, it represents a significant issue when trying to study a complex and visually demanding activity such as driving (60). A recent study by Cuenen et. al. (22) has suggested that different aspects of driving behavior are better predicted by specific perceptual and cognitive “functional” abilities. 3D-MOT has proven to be an integrative measure of several of these different abilities (81). This highlights not only the link between attentional function and driving but also suggests the importance of incorporating a dynamic assessment of sustained visual attention when studying driving performance.

A recent meta-analysis by Vanlaar et. al. (82) reports robust evidence that suggests that cognitive screening instruments have value in predicting driving ability, although at present there is no single instrument that can accurately identify an unsafe driver. The well-known test traditionally used to assess attention through the visual field and, thus, aspects of driver safety, is the Useful Field of View (UFOV). One of the main limitations of this test is that it does not directly assess dynamic processing, unlike MOT. Our results from the correlational and regression analysis suggest that NeuroTracker speed threshold measures may be comparable to results obtained by Cuenen et. al. (83) for UFOV in predicting specific aspects of driving ability (e.g. mean driving speed). Future research should compare NeuroTracker thresholds more directly with the UFOV as well as other tests of perceptual-cognitive function to evaluate its effectiveness as a more integrative predictor of driving risk.

Conclusion

Our experiment was designed to determine the efficacy of different scenarios to elicit naturalistic driving behavior across different age groups. Insights from this study provide a justification for several different improvements of future cross-sectional driving research as well as new insights into how subtle changes in perceptual-cognitive abilities might impact specific aspects of driving behaviour. For instance, study designs should include appropriate scenario selection and driving task complexity to reduce the variability of naturally adopted driving speeds. This finding provides a rationale for future research to use more overt methods (i.e. sensory feedback) to encourage participants to drive at more uniform mean speeds alongside statistical methods of controlling for such variability. Additionally, new driving behavior measures developed in this study may be used to account for inappropriate driver actions.

Notably, higher 'Max brake' and 'Max steer change rate', as well as decreased distances from the hazards at which both of these extreme behaviours took place, emerged as possible indicators of at-risk driving. These novel measures of uncontrolled and abrupt driving maneuvers warrant further investigation and inclusion alongside more traditional measures of driving ability. And finally, perceptual-cognitive measures can help quantify the underlying factors of diminished driving performance—notably, helping to identify participants that might be engaging in compensatory driving behaviour but still at increased risk. Such a result is in line with established literature and provides an impetus for further study into how these mental faculties can be used both for identifying and possibly helping drivers with diminished driving.

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Competing interests

Jocelyn Faubert is director of the Visual Psychophysics and Perception Laboratory at the University of Montreal and he is the Chief Science Officer of CogniSens Athletics Inc. who produce the commercial version of the 3D-MOT program (NeuroTracker) used in this study. In this capacity, he holds shares in the company. Pierro Hirsch is a road safety researcher and driver training program developer at Virage Simulation Inc. who produces the commercial version of the driving simulator (VS500M) used in this study. Delphine Bernardin and Guillaume Giraudet are associated professors of the NSERC/Essilor Chair at the University of Montreal and are both employed by Essilor as research project managers. No author listed in the statement above contributed to data collection or analysis.

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Article 2 – Three-dimensional multiple object tracking improves young adult cognitive abilities associated with driving: evidence for transfer to the Useful Field of View

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Abstract

Objectives: 3-dimensional multiple object tracking (3D-MOT) and the Useful Field of View (UFOV) both claim to measure and train cognitive abilities such as selective and divided attention implicated in driving safety. 3D-MOT is claimed to improve even young adult cognitive ability. If true, one would expect to observe transfer of 3D-MOT training to UFOV performance mediated by way of shared underlying cognitive mechanisms. **Methods:** We test this notion by assessing whether ten 30-minute sessions of 3D-MOT training spread across five weeks improves UFOV performance relative to an active control group trained on a visual task and a challenging puzzle game (participants aged between 23 and 33 years old). **Results:** The 3D-MOT training group exhibited significantly improved UFOV performance whereas the active control group exhibited only a small, statistically non-significant improvement in the task. **Conclusions:** This suggests that 3D-MOT and UFOV performance are likely dependent on overlapping cognitive abilities and helps support the assertion that these abilities can be trained and measured even in young adults. Such training could have implications for improving driver safety in both young and older adults.

Keywords: three-dimensional multiple object tracking speed task, useful field of view, transferability, perceptual-cognitive training, attention, driving

Introduction

Multiple object tracking (MOT) is an experimental paradigm originally developed by Pylyshyn & Storm (1) to study visual attention and the human capacity to simultaneously track multiple moving objects while ignoring distractors. Faubert & Sidebottom (2) later adapted this paradigm into a perceptual-cognitive training program called 3-dimensional multiple object tracking (3D-MOT) implemented in commercially available software known as NeuroTracker. Research has implicated sustained and distributed attention (3,4) and visual working memory processes (5) during MOT tracking but the purported benefits of such training are still under investigation.

The speed at which individuals can reliably track multiple targets can be increased through training (2). Hypothesized benefits of such training are numerous: from delaying age-related deficits in cognitive function to improving the attentional function of healthy adults and individuals with attentional disorders. Increased tracking speed alone does not unambiguously support the idea that the attentional processes solicited during 3D-MOT improve more generally, however. Indeed, in 2014 the Stanford Center on Longevity and the Berlin Max Planck Institute for Human Development issued a joint statement highlighting the need for additional systematic research investigating the potential benefits of software-based cognitive training programs (6). They stressed the importance that learning, “should not be restricted to the acquisition of a specific skill but should instead be measurable in an array of tasks linked by their reliance on a particular ability.” To this point, a large and growing body of literature suggests that 3D-MOT training transfers to fundamental cognitive abilities such as attention and working memory span along with numerous real-world behaviours whose performance is underpinned by effective attentional function (7–12). Results from studies using other computerized cognitive training programs such as the Useful Field of View (UFOV) provide further support, but continued research is necessary to address all the limitations highlighted by the joint statement.

The UFOV has emerged as a gold standard for assessing attentional ability in the elderly, especially in driving safety contexts. Ross et al. investigated whether speed of processing training had an impact on driving cessation rates across ten years in the context of the large-scale, multisite Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) study (13). They found that such training reduced the likelihood that drivers defined as at-risk for future mobility declines quit driving in the following ten years. Additionally, it was found that individuals that underwent this training had a 28% reduced risk of developing dementia in the ten years that followed relative to controls (14). While the UFOV is frequently referred to as a test of visual speed of processing, two of its three subtests (UFOV2 and UFOV3) implicate selective and divided attention through the introduction of a secondary peripheral detection task and peripheral distractors in the third subtest. This additional attentional demand may explain why a meta-analysis by Woutersen et al. (15) found strong correlations between UFOV3, visual speed of processing and attention. Their analysis suggests that UFOV3 performance may be even more related to attentional ability than it is to visual speed of processing.

Given this link between attentional function and UFOV ability, one should expect that cognitive training aimed at improving the specific forms of attention solicited by UFOV subtests, if successful, should be reflected by improved UFOV performance. Such a finding would provide additional convergent validity for the claims of both 3D-MOT and UFOV training programs. Few studies have probed the link between 3D-MOT training and UFOV ability. Thus, the purpose of the present study is to determine whether or not 3D-MOT training transfers to UFOV performance in young adults.

Methods

Participants

Twenty young adults between the ages of 23 and 33 (mean = 28.5 ± 3.97) were recruited and randomly assigned to either a 3D-MOT training (EXP; n = 10) or active control group (CON; n = 10). All participants were told that they were recruited to test the effectiveness of a novel computer-based cognitive training program, were naïve to all training tasks in the study, and had normal or corrected-to-normal vision. They were free of visual, sensory, motor and neurological impairments as well as any diagnosis of neurodevelopmental disorders. The study adhered to the tenets of the Declaration of Helsinki (last modified, 2013), all tests and procedures were approved by the ethics committee of the Université de Montréal (CERES; Comité d'éthique de la recherche en santé certificate nº 16-130-CERES-D).

Stimuli and procedure

The pre- and post-training evaluations each lasted approximately two hours. Measures of visual discrimination, Useful Field of View (UFOV) and 3D-MOT ability were taken in both pre- and post-training sessions. The training phase of the study occurred between these two evaluations.

All participants were required to travel to the laboratory for ten 30-minute training sessions at a rate of two per week for five weeks. Thus, the total training duration was 5 hours per participant. The experimental group's training sessions consisted of three series of twenty 3D-MOT trials. By comparison, the active control group underwent an alternate training of three series of a visual discrimination task and the challenging open-source puzzle game *2048* (https://play2048.com/) during their sessions. All participants were completely new to 3D-MOT and *2048*.

Experimental group: 3D-MOT

The task involved simultaneous tracking of four linearly moving, dynamically interacting spherical targets among four identical distractors for a continuous eight seconds. The stimuli were displayed on a 65-inch Panasonic 3D TV screen and subjects wore Panasonic active shutter 3D glasses while being seated on a chair placed 150cm from the screen. Each trial can be broken down into five phases (Figure 7). If a participant was able to successfully track all four targets, then the trial was registered as successful and the movement speed of the stimuli in the following trial increased. Otherwise, stimuli speed was decreased. These changes followed a 1-up 1-down adaptive staircase protocol (16) that varied speeds more greatly for early inversions than later ones in order to quickly identify the optimal speeds to train each participant. Performance on the task was defined by a final tracking speed threshold after 20 trials. The three series' values were subsequently averaged in order to have a final value for each session.

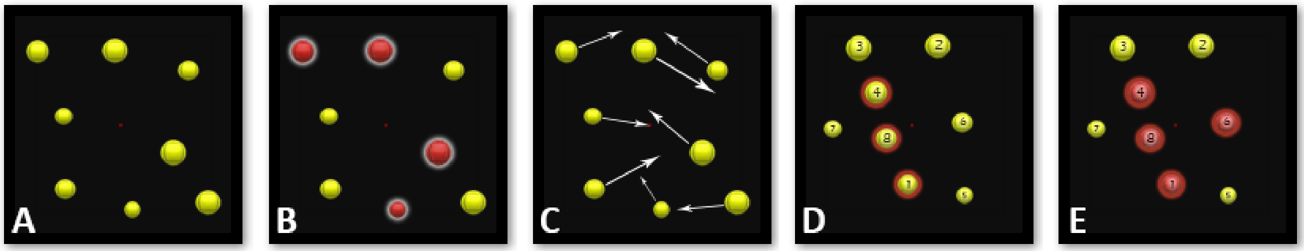

Figure 7. – The five phases of a 3-dimensional multiple object tracking trial.

Active control group: visual discrimination and 2048

The first task used for the alternate training was a simple first-order, i.e. luminance-defined forced-choice orientation discrimination task using sine-wave gratings (see (7) for a description). Participants were required to identify if the sine-wave grating was displayed with either a vertical or horizontal orientation. They were subsequently provided with auditory feedback indicating if they were correct or not. The stimuli's luminance was modulated following a 2-up 1-down staircase procedure and the minimum luminance threshold obtained for the stimulus discrimination was estimated from the last six reversals of the staircase. This task was chosen because of its potential to induce perceptual learning without expected transfer to an attention-oriented task like UFOV (17).

Following three series of the discrimination task, the last remaining fifteen minutes in each 30-minute training session was spent by having active control participants play *2048*. It's a simple to understand math-like puzzle game whose use as an active control task for the 3D-MOT task has previously been described in the literature (9). The display and seating distance were identical to the experimental task.

Outcome measures

UFOV

The test consists of three subtests, intended to measure: 1. Processing speed, 2. Processing speed under divided attention conditions and, 3. Processing speed under selective attention conditions (18). Scores ranged from 16.7ms to 500ms for each subtest, representing the minimum display duration thresholds at which participants could perform each task as determined by an adaptive two-step size staircase. Thus, a lower score reflects better performance. Participants were seated 24 inches away from a 17" eMachines monitor with 1024 x 768 resolution and a 60 Hz refresh rate. UFOV7 software was used for all testing.

Statistical analyses

One significant outlier in the control group was identified using boxplots of pre-training UFOV scores and removed from subsequent analyses (following (19)). We added participants' UFOV scores across all three subtests as young adults tend to exhibit floor effects[2] with very little variability on the first two subtests (20), and conducted statistical analyses on total UFOV scores after confirming that this aggregate measure did not violate the assumption of normality. In order to compare post-training 3D-MOT, UFOV and perceptual discrimination task improvement between both groups, we conducted univariate analysis of covariance (ANCOVA) tests with pre-training scores entered as a covariate (following recommendations of (21)). *2048* performance change was analyzed by way of a paired samples t-test on first and last training session highest scores.

Results

3D-MOT training improves UFOV ability

As shown in Table 7, independent samples t-tests revealed no significant group differences in pre-training 3D-MOT absolute thresholds [$t(17) = 0.07$, $p = 0.95$], perceptual discrimination [$t(17) = -0.84$, $p = 0.42$] or UFOV performance [$t(17) = -1.06$, $p = .97$]. Figure 8 shows that 3D-MOT scores were significantly better in the experimental group compared to the active control group

[2] As UFOV scores represent minimum display duration detection thresholds, a "floor effect" reflects excellent performance in this context.

following training [F(1,16) = 16.65, p < 0.001, η_p^2 = 0.51]. Similarly, a paired samples t-test comparing control group pre-training *2048* (M = 2601.33, SD = 529.25) and post-training (M = 5510.67, SD = 2158.13) performance revealed a statistically significant improvement [t(8) = -3.805, p = 0.005]. As shown in Table 7, between-group post-training perceptual discrimination scores differed in absolute terms which may suggest that perceptual learning occurred in the control group, but this difference was not statistically significant [F(1,16) = 2.81, p = 0.11, η_p^2= 0.15]. Considering that the static, first-order grating stimuli employed are generally used to test low-level visual processing, a floor effect could be involved. It is also possible that the study simply lacked sufficient statistical power to establish that this learning occurred. The observed improvements in experimental 3D-MOT and control *2048* performance demonstrate that both groups were actively engaged in their respective training sessions. Finally, we looked at scores on the untrained UFOV task. Levene's test was not significant [F(1,17) = 0.03, p = 0.87] indicating that the assumption of homogeneity of variance had not been violated. The experimental group demonstrated significantly greater post-training UFOV performance relative to the control group [F(1,16) = 6.52, p = 0.02, η_p^2 = 0.29].

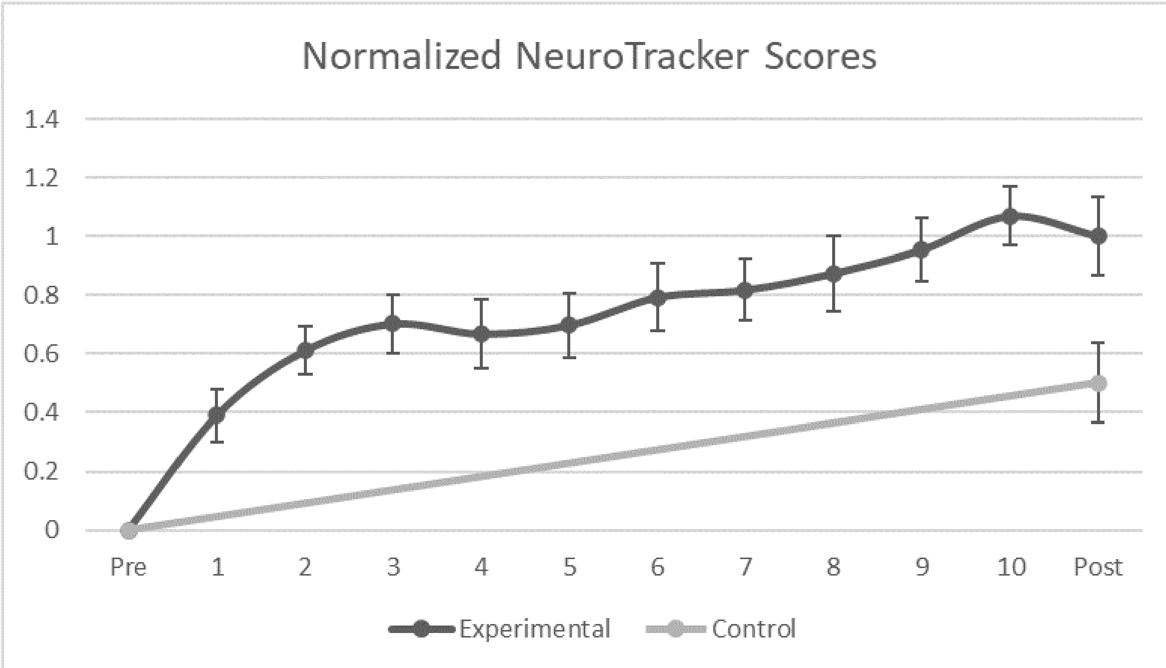

Figure 8. – Normalized learning curves (session scores – initial score) with group means and standard error bars for 3D-MOT.

Table 7. – Summary of the experimental group (EXP.) and control group's (CON.) mean pre- and post-training data with one standard error (±).

	Experimental Group (n = 10)			Control Group (n = 9)			
Measure	**Pre**	**Post**	**Change**	**Pre**	**Post**	**Change**	**Significance**
3D-MOT	1.04±0.12 z = 0.016	2.01±0.17 z = 0.59	0.97±0.12 Δz = 0.58	1.03±0.15 z = -0.15	1.40±0.12 z = -0.66	0.37±0.09 Δz = -0.51	**< 0.001**
UFOV Total	92.62±9.17 z = -0.24	73.68±7.60 z = -0.55	-18.94±7.82 Δz = -0.31	106.72±9.6 z = 0.26	102.51±6.11 z = 0.61	-4.21±10.48 Δz = 0.35	**0.02**
Perceptual Discrimination	0.023±0.002 z = -0.189	0.021±0.002 z = 0.34	-0.002±0.002 Δz = 0.53	0.036±0.016 z = 0.21	0.017±0.002 z = -0.38	-0.02±0.016 Δz = -0.59	0.11

Within-group mean change scores and p-values for between-group comparisons are also provided. Z-scores computed from aggregated Experimental and Control data are provided below each raw score to ease comparison across different measures and their relative change post-training. 3D-MOT scores represent maximum log displacement speed thresholds at which the four targets could be successfully tracked. UFOV scores represent the sum of UFOV subtest 1-3 minimum stimulus duration thresholds in milliseconds. Perceptual discrimination scores represent the threshold contrast required to discriminate horizontal vs. vertical Gabor patches.

Discussion

The present study suggests that UFOV and 3D-MOT both tap into common underlying cognitive abilities and that 3D-MOT training improved one or more of these abilities such that it transferred to UFOV performance. Given the important role of attention in both 3D-MOT and the UFOV subtest 3, one possible interpretation is that the present results are explained by enhancement of shared attentional processes. UFOV3 is claimed to solicit selective and divided attention: both of which underlie MOT ability. Previously, this had been demonstrated in specific clinical populations such as individuals with multiple sclerosis (22). The present study demonstrates similar transfer in young adults and against an active control group. As such, one may expect some overlap in the potential applications of UFOV and 3D-MOT assessment and training. Indeed, recent evidence suggests that 3D-MOT is useful for identifying at-risk drivers in a similar fashion to the UFOV but in both young and older adults alike (23,24). It has even been suggested that the more dynamic nature of MOT implicates additional cognitive abilities such as sustained attention, which may improve its predictive power vis-à-vis accident propensity (25). It is as-of-yet unknown whether 3D-MOT training offers the same reported long-term protection against driving cessation and dementia but the current results provide a strong rationale for further investigation.

Conclusion

We have successfully demonstrated transfer of cognitive training to another task designed to measure similar cognitive abilities. This result offers convergent validity for UFOV and 3D-MOT and provides further rationale for exploring 3D-MOT's potential as an evaluation of driver safety.

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Conflicts of Interest

Jocelyn Faubert is the inventor of the commercial version of the multiple object tracking task used in this study, NeuroTracker. In this capacity, he holds shares in the company.

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Article 3 – Can three-dimensional multiple object tracking training be used to improve simulated driving performance? A pilot study in young and older adults

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Abstract

Driving ability has been shown to be dependent on perceptual-cognitive abilities such as visual attention and speed-of-processing. There is mixed evidence suggesting that training these abilities may improve aspects of driving performance. This preliminary study investigated the feasibility of training three-dimensional multiple object tracking (3D-MOT)—a dynamic, speeded tracking task soliciting selective, sustained and divided attention as well as speed-of-processing—to improve measures of simulated driving performance in older and younger adults. A sample of 20 young adults (23-33 years old) and 14 older adults (65-76 years old) were randomly assigned to either a 3D-MOT training group or an active control group trained on a perceptual discrimination task as well as *2048.* Participants were tested on a driving scenario with skill-testing events previously identified as optimal for cross-sectional comparisons of driving ability. Results replicated previously identified differences in driving behaviour between age groups. A possible trend was observed for the 3D-MOT trained group, especially younger adults, to increase the distance at which they applied their maximum amount of braking in response to dangerous events. This measure was associated with less extreme braking during events, implying that these drivers may have been making more controlled stops. Limitations of sample size and task realism notwithstanding, the present experiment offers preliminary evidence that 3D-MOT training might transfer to driving performance through quicker detection of or reaction to dangerous events and provides a rationale for replication with larger sample size.

Keywords: Multiple object tracking (MOT), driving, cognitive training, speed-of-processing, attention

Conflict of Interest

Jocelyn Faubert is director of Faubert Lab at the University of Montreal and he is the inventor of the commercial version of the multiple object tracking task used in this study, NeuroTracker. In this capacity, he holds shares in the company.

Acknowledgments

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Introduction

Driving is undoubtedly a highly complex task. While experienced drivers can often be fooled by the relative ease with which they control their vehicles, this performance is subserved by a panoply of sensory, motor, and cognitive systems working in concert (1). Indeed, research has now come to emphasize the importance of perceptual-cognitive abilities such as visual attention, visuospatial skills, and speed-of-processing above purely visual sensory measures in relation to driver safety (2-6). Such research is typically conducted in older adult populations due to their well-established declines in components of attention (7-9) and speed-of-processing (10,11). As discussed by Zicat et al. (12), this relationship between safety and perceptual-cognitive ability has often been neglected in research on younger drivers; they found that such abilities accounted for driving performance even in young adults and even while accounting for personality traits and driving attitudes. Similarly, Backs et al. (13) also found that attention explained driving performance variance in a large sample of varying age groups. Nonetheless, studying the ageing driver context is crucial due to the ongoing demographic shift occurring in industrialized countries (14) and findings suggesting that some older adults may be at an elevated risk of accidents relative to middle-aged drivers (15,16,19).

An impressive body of literature on the Useful Field of View (UFOV)—a computerized measure of selective and divided attention as well as speed-of-processing—demonstrates that deficits in these functions is predictive of long-term negative driving outcomes such as driving errors (18), crash involvement (19-21) and eventual driving cessation (22-25). UFOV and other measures of decreased speed-of-processing have also been linked to increased driver self-regulation (26,27) and driving errors (28). Additionally, research demonstrates that UFOV is capable of predicting simulated and on-road driving performance in experimental studies (29,30). While predicting differences in driving performance and outcomes is already an impressive feat, some research has suggested that training aimed at improving UFOV may actually enhance driver safety. Roenker et al. (31) showed that speed-of-processing training resulted in improved driving performance in a simulator and decreased reaction times. A longitudinal study by Ross et al. (25) found decreased driving cessation among individuals at-risk for future mobility declines following training and booster sessions. Such results are not consistent, however, as both Gaspar et al. (32) and Tsotsos et al. (33) did not observe any improvements related to training. This is perhaps unsurprising considering how complex a task driving is and the multitude of methods one could use to quantify its performance. That said, the great social value of maintaining road safety for all offers a clear impetus to continue evaluating whether such training can indeed transfer to measures of driving performance.

Recently, we and two other groups of researchers demonstrated that attentional ability and speed-of-processing measured by three-dimensional multiple object tracking (3D-MOT) could also predict measures of simulated driving performance (34-36). The version of the task used—which assesses the speed at which individuals can simultaneously track and attend to multiple moving objects amidst identical distractors—was implemented using commercially-available technology known as NeuroTracker™. It has a number of differences compared to the UFOV: most notably, it assesses dynamic attention unlike the static stimuli of the UFOV. Additionally, its difficulty is more adaptable to a wide range of populations and individual baselines (37).

3D-MOT training has been shown to enhance young adult selective and distributed attention, visual information processing, and working memory function measured through neuropsychological tests and changes in associated quantitative electroencephalographic activity (38). It has also been shown to transfer to UFOV performance in young and middle-aged adults (39,40), improve passing decision-making accuracy in soccer players (41), boost working memory span in military populations (42), and improve attention in students with neurodevelopmental conditions (43). However, unlike with UFOV training, no study has ever evaluated possible transfer to driving performance following this training paradigm. Thus, we decided to investigate whether 3D-MOT training could produce a measurable effect on performance of a simulated driving task.

2. Materials and Methods

2.1 Participants

To investigate training outcomes as well as the potential effect of age on training outcomes, we assessed 32 young adults (YA) and 44 older adults (OA) for eligibility. As shown in Figure 1, if a participant was found to be eligible, they were randomized into either an experimental (EXP; $n_{EXP} = 23$) or active control group (CON; $n_{CON} = 22$) via a computer randomization script. As a result of the global COVID-19 pandemic necessitating an early termination of the study as well as participant attrition, our final sample consisted of 20 young adults (YA) that were 23-33 years old and 14 older adults (OA) that were 65-76 years old ($N = 34$; $N_{YA} = 20$, $N_{OA} = 14$) distributed in equal quantity to experimental and active control groups ($n_{EXP} = 17$, $n_{CON} = 17$). The young adult experimental and active control groups were statistically similar in age (M_{YA}±SD = 27.5±3.21 vs. 29.1±2.77), sex ratio ($n_{YAfemale}$ = 5 vs. 4), and years licensed to drive (M_{YA}±SD = 8.6±3.6 vs. 9.8±4.34). The same was true for older adult age (M_{OA}±SD = 70.43±3.69 vs. 68.0±3.37), sex ratio ($n_{OAfemale}$ = 3 vs. 2), and years licensed (M_{OA}±SD = 53.43±5.09 vs. 52.57±4.12). Regardless of randomization, participants were told that they were recruited to test the effectiveness of a computer-based perceptual-cognitive training program.

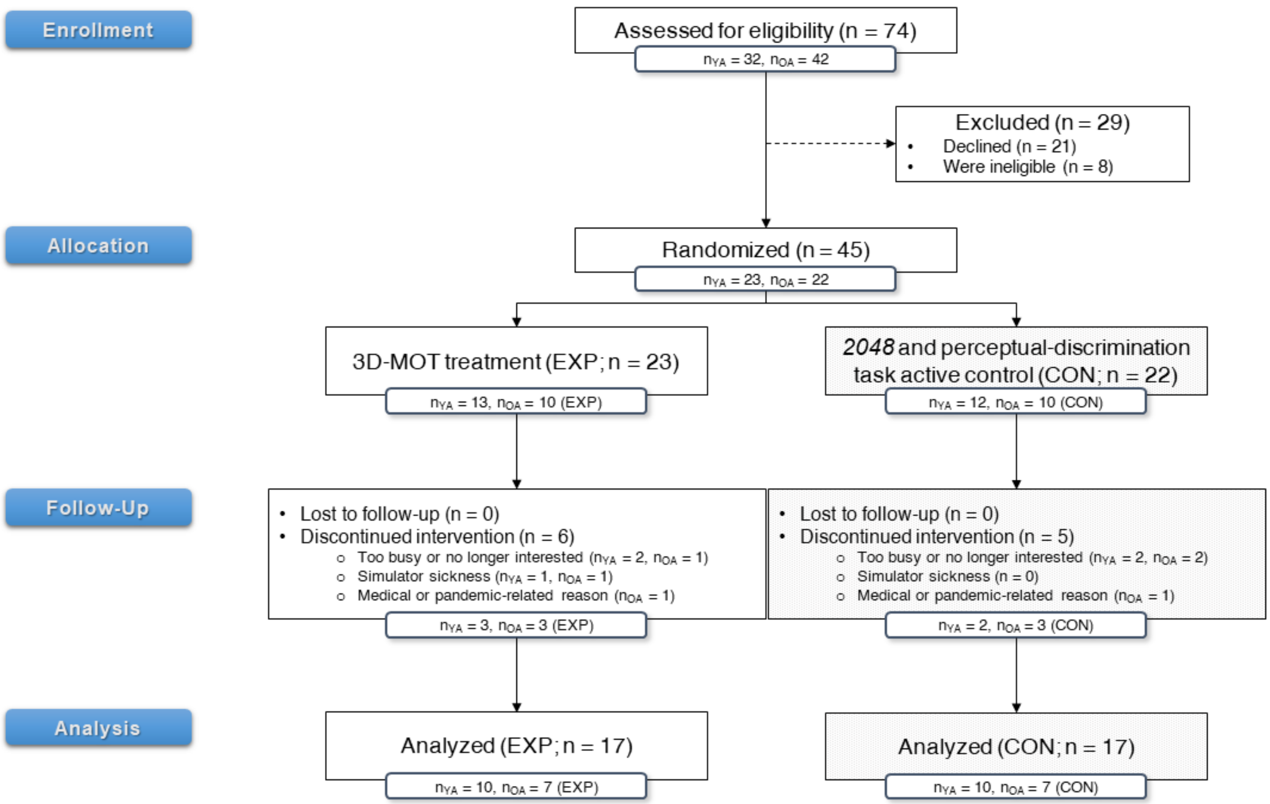

Figure 9. – Flow diagram outlining participant inclusion and randomization process. Sample size information about young adult (YA) and older adult (OA) and their distribution in experimental (EXP) and active control (CON) treatments is provided for each step.

All participants had normal or corrected-to-normal vision, consisting of: visual acuity score of 6/7.5 or better with both eyes using an ETDRS chart, stereoscopic acuity of 50 seconds of arc or better using the Randot test and a normal visual field using a Humphrey visual field analyzer. Additionally, all participants had a normal score (≥26/30) on the Montreal Cognitive Assessment (MoCA) suggesting no mild cognitive impairment. They were free of visual, sensory, motor, and neurological impairments as well as any diagnosis of neurodevelopmental disorders, and all possessed a valid driver's license for a minimum of five years. The study adhered to the tenets of the Declaration of Helsinki (last modified, 2013), all tests and procedures were approved by the ethics committee of the Université de Montréal (CERES; Comité d'éthique de la recherche en santé certificate nº 16-130-CERES-D). All volunteers signed forms indicating informed consent and received a compensation of $15 at the end of each session.

2.2 Outcome measures

2.2.a Apparatus

To evaluate participants' driving performance when faced with dangerous situations, a VS500M car driving simulator (Virage Simulation Inc.®) was used for all driving sessions. It is a high-fidelity motion platform driving simulator that uses real car parts in the cockpit, including: a seat, force feedback steering wheel, dashboard, controls, indicators, automatic transmission as well as accelerator and brake pedals. Three 1280x720 pixel 50-inch plasma screens provided a 180º front field of view while two smaller screens placed laterally and behind the cockpit replicated the car's blind spots. Rear-view and side mirrors were digitally rendered in the front screens to approximate their physical locations in a real car. Additionally, motion and sound cues were used to enhance realism and immersion even further. The driving cabin was mounted on a three-axis platform with electric actuators that recreated the haptic feedback of acceleration, braking, engine vibration and road texture as a function of driving speed. Naturalistic engine and surrounding road sounds were recreated via a stereo sound system and Doppler shifts were applied to the sounds of passing traffic as a function of driving speed.

2.2.b Scenario and driving measures

Driving simulator validity is highly dependent on proper scenario and driving measure selection and this is especially true in the context of cross-sectional research (44-46). Thus, we elected to reuse the same Rural scenario and driving measures previously described in our previous large-scale methodological study (34). Compared to the alternatives, the Rural scenario was shown to be the most sensitive to well-described age differences in driving performance as well as the best at eliciting realistic driving behaviours. This scenario was designed to be of moderate complexity and mental workload, following the work of Paxion et al. (47) that analyzed driving situation complexity and mental workload in terms of different road designs, layouts and traffic densities. It contained sections of road with three different speed limits: 90, 70 and 50km/h. Participants were instructed to drive as naturally as possible while respecting the posted speed limits, road signage and other drivers, and to follow visual and auditory navigational instructions provided by the scenario. To reduce previously identified mean driving speed variability between older and younger adults while still allowing participants full control over the vehicle, auditory feedback was provided to participants if their driving speed surpassed or fell below the posted speed limits by more than 5km/h. This feedback took the form of unobtrusive high and low pitch tones (for above and below the speed limit, respectively) that obviated the need for participants to shift their gaze from the road. Participants were instructed to use these cues and the three different posted speed limits to maintain a reasonable driving speed except in situations where they needed to respond to on-road situations. To have a large enough sample of each participant's driving behaviour, performance was averaged across seven skill-testing events that were triggered at pre-programmed locations along the route. These events required evasive maneuvers or sudden braking to navigate safely without collisions. The scenario included both single-phased (i.e., the hazard is always visible) and two-phased materialized hazards (i.e., the hazard is hidden before becoming visible) following the event typology described by Borowsky & Oron-Gilad (48). Two variants of this scenario were programmed with the location of events shuffled around to reduce any learning effects from pre to post. Presentation of each variant in either pre- or post-training was randomized and counterbalanced across subjects to control for any unintended bias in task difficulty.

As summarized in Table 8, a total of nine measures were previously identified as pertinent and non-redundant descriptors of driving performance in the Rural scenario (34). Additionally, correlation and multiple linear regression analysis demonstrated links between 3D-MOT performance and a number of these measures. Thus, we hypothesized that if perceptual-cognitive training can improve cognitive abilities involved in driving safety, it would be most detectable through these measures.

Table 8. – Definition of the most pertinent measures identified by Michaels et al. 2017 and the units in which they were recorded.

	Measure	Unit	Description
1	**Crash**	*n*	Whether a collision occurred or not during the event.
2	**Near Crash**	*n*	When within an event: • Subject brakes harder than a given threshold while driving at a speed greater than 5 m/s (18km/h) • The steering wheel is turned more than 60 degrees while driving faster than a speed threshold (5 m/s) • The participant drives within 3m of an object while travelling at a speed greater than 10m/s (36km/h).
3	**Mean Speed**	*km/h*	Average speed of all driving. Data points where speed was inferior to 10km/h or recorded 300m before and 100m after an event were discarded from the averaging.
4	**SDLP**	*m*	Standard deviation of lateral position. Identical exclusion criteria as mean driving speed were applied. Additionally, for each data point, lateral positions recorded 10 seconds before and after a lane change were excluded from the averaging.
5	**Max Brake**	*n*	Hardest amount of braking applied during event of interest. Ranges between 0 (= no braking applied) and 1 (= brake pedal is fully depressed)
6	**Distance at Max Brake**	*m*	Distance from event of interest at which "Max brake" is recorded.
7	**Max Steer Change Rate**	*º/s*	Most extreme (in terms of range and speed) left or right steering wheel position change during event of interest.
8	**Distance at Max Steer Change Rate**	*m*	Distance at which "Max steer change rate" is recorded during event of interest.

9	**Steer Range**	º	Difference in degrees between leftmost and rightmost steering wheel position for event of interest.

n corresponds to an undefined unity, *km* to kilometers, *h* to hours, *m* to meters, º to degrees, and *s* to seconds.

2.2.c Attention and speed-of-processing: the UFOV test

As previously discussed, research has demonstrated significant correlation between UFOV and MOT ability (36). It has been previously remarked that performance of 3D-MOT and UFOV is likely subserved by common cognitive processes such as divided and selective attention as well as speed-of-processing (40). Considering the established literature demonstrating the utility of UFOV as a predictor of driving performance and the evidence that it may improve driver reaction time, we elected to include the UFOV version 7 as an additional mid-level transfer outcome measure of 3D-MOT training. To date, no study has demonstrated transfer of 3D-MOT training to UFOV performance in healthy older adults.

2.3 Protocol

The study was divided into three phases occurring over a period of seven weeks: 1. The pre-training phase (week 1), 2. The training phase (weeks 2-6) and 3. The post-training phase (week 7).

The first of these phases was identical for all subjects and consisted of two in-person sessions separated by a minimum of two days. The first of these consisted of a visual exam including the ETDRS (Early Treatment Diabetic Retinopathy Study) visual acuity test, Humphrey visual field test as well as the Randot stereoacuity test meant to screen any drivers with uncorrected visual deficits. Additionally, participants were screened for mild cognitive impairment using the MoCA. They were interviewed to confirm that they were never diagnosed with neurodevelopmental disorders or untreated health problems affecting their equilibrium or heart. All were free from neurodegenerative diseases, diabetes and were not routinely taking any medications that could affect their vigilance or attention. Finally, all participants confirmed that they had never previously participated in any research studies on driving and that they held a driver's license for a minimum of five years. Following the screening step, participants' visual processing speed was assessed using the UFOV. At the end of this session, participants all tried the driving simulator in an unrecorded twelve-minute driving session consisting of two six-minute-long highway driving scenarios without skill-testing events. This initial introduction was done to allow participants to become familiar with the handling of the vehicle before testing sessions and because it has been shown to reduce the effects of Simulator Adaptation Sickness (50). The second pre-training session included an assessment of baseline 3D-MOT tracking speed and perceptual discrimination thresholds. As all participants were naïve to both tasks, they were first read instructions by the experimenter and given six practice trials of 3D-MOT prior to the actual assessment to make sure they understood the instructions. Following these tests, participants were tested on the driving simulator. The presence and severity of simulator sickness symptoms was measured before and after each driving test via the Simulator Sickness Questionnaire (SSQ) and change scores were computed to determine the effects of the simulator (51).

During the second phase, all participants were required to travel to the laboratory for ten 30-minute training sessions twice per week for five weeks (5 hours total). This number of sessions and session duration was selected as it has been previously used to successfully demonstrate transfer in young adults (41). As previously described, the experimental group's training sessions consisted of three series of twenty 3D-MOT trials while the active control group underwent an alternate training of three series of a visual discrimination task followed by fifteen minutes of *2048*. The experimenter read the rules of *2048* to participants in the active control group at the first training session and demonstrated how to use the keyboard arrows to control the movement of the tiles until participants clearly understood the control scheme and goal of the game.

The post-training phase consisted of a final two sessions mirroring the pre-training phase. The first of these included post-training 3D-MOT and perceptual discrimination measures and the second was dedicated to post-training driving simulator assessment using whichever variant of the Rural scenario was not previously assigned at the pre-training driving test.

2.4.a Three-dimensional multiple object tracking (EXP; experimental group)

The 3D-MOT task requires simultaneous tracking of four randomly moving, dynamically interacting spherical targets whilst simultaneously ignoring four identical distractors for a continuous eight seconds. The stimuli were displayed on a 65-inch Panasonic 3D TV screen. Subjects wore Panasonic active shutter 3D glasses while being seated on a chair placed 150cm from the screen. As depicted in Figure 10, each trial can be broken down into five phases. If a participant was able to successfully track and identify all four targets, then the trial was registered as successful and the movement speed of the stimuli in the following trial increased. Otherwise, stimuli speed was decreased. These changes followed a 1-up 1-down adaptive staircase protocol (52) that varied speeds more greatly for early inversions than later ones in order to quickly identify the optimal speeds to train each participant. Correct or incorrect responses on each trial resulted in a proportional speed increase or decrease of 0.05 log units, respectively. Performance on the task was defined by a final tracking speed threshold computed based on the last four reversals of the staircase. Participants completed three series of 20 trials and the three tracking speed thresholds were subsequently averaged and log transformed to have a final value for each session.

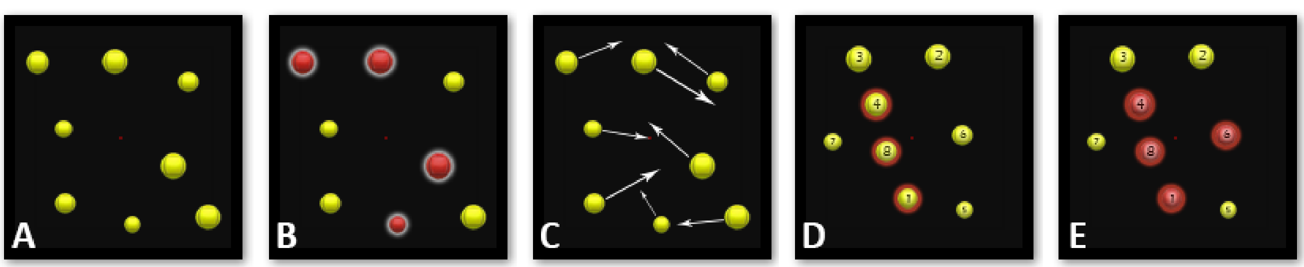

Figure 10. – The five phases of a 3-dimensional multiple object tracking trial: (A) Eight identical spheres are randomly positioned in a virtual cube. (B) The four target spheres are identified by becoming temporarily highlighted. (C) The target spheres revert to their standard appearance and all spheres begin randomly moving along linear paths within the virtual cube. (D) The spheres stop moving and gain numerical labels to allow participants to identify the target spheres. (E) The correct spheres are highlighted and additional auditory feedback is provided.

2.4.b Perceptual discrimination & *2048* (CON; active control group)

As shown in Figure 11, participants in the active control group all practiced two different tasks. The first of these tasks used for the alternate training was a simple first-order (i.e. luminance-defined), forced-choice orientation discrimination task using sine-wave gratings (see (53) for a description). Using stimuli like those shown in Figure 11a, participants were required to identify if the sine-wave grating was oriented either vertically or horizontally by pressing the up-arrow key or right arrow key, respectively. They were provided with auditory feedback indicating whether their response was correct or not after each trial. The gratings' luminance was modulated following a 2-up 1-down staircase procedure and the minimum contrast threshold for stimulus orientation discrimination was estimated from the last six reversals of the staircase. This task was selected for its potential to demonstrate low-level perceptual learning without expected transfer to higher-level cognitive functions solicited by 3D-MOT.

Following three series of the discrimination task, the last remaining fifteen minutes in each thirty-minute training session was spent by having active control participants play the challenging open-source puzzle game *2048* (https://play2048.com/) shown in Figure 2b. Its use as an active control task for 3D-MOT has previously been described in the literature (43). Additionally, the easy-to-grasp rules and simple control scheme makes the task particularly well-suited for older and younger adults alike. Once a participant could make no more valid moves (i.e., they had a "game-over") their score was noted to track their progress. The highest score achieved was used for analyses if a participant played multiple rounds in a single session. The display and seating distance for both active control tasks were identical to the experimental task.

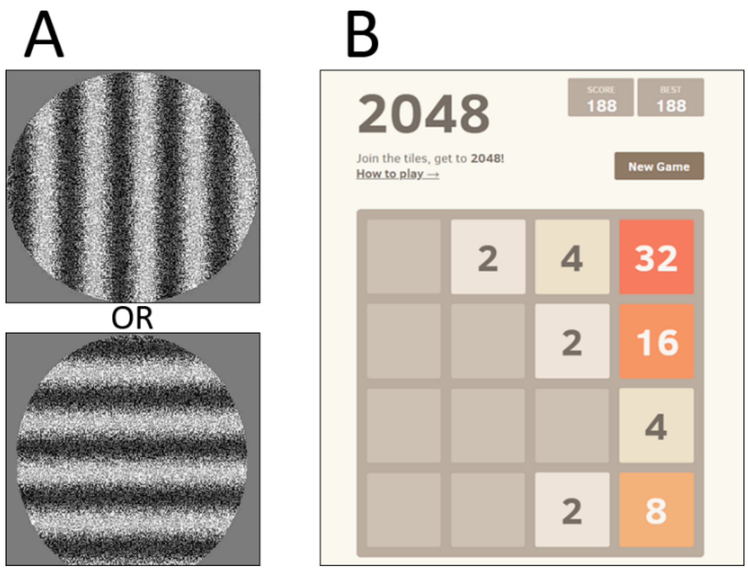

Figure 11. – The two training tasks used in the active control group. (A) Examples of the stationary vertical and horizontal Gabor patches presented in the orientation perceptual-discrimination task before any modulation of contrast. Participants were forced to choose whether each stimulus presented was oriented either vertically or horizontally and correct answers resulted in subsequent presentations having decreased Michelson contrast and vice versa. (B) The 4x4 game grid and example tiles for 2048. Players interact with the game solely via the four arrow keys to slide all the current game tiles in the chosen direction and then a new 2 or 4 tile is randomly added to the grid. When two identically-numbered tiles collide, they combine to form the next highest factor of 2048, and the player's score is increased by the value of that tile. The goal of the game is to create a 2048 tile and/or to achieve the highest possible score before the entire grid fills up in a configuration that blocks any further moves.

2.5 Statistical analysis

We first conducted preliminary analysis on the intervention and outcome measures to check the data distributions and to examine if baseline results were consistent with past observations. Two extreme outliers were detected (n_{YA_CON} = 1, n_{OA_EXP} = 1) using boxplots of pre-training and post-training perceptual discrimination scores (following (54)) and those data were removed from subsequent analysis involving that measure. As the UFOV task used in this study consists of 3 subtests, a composite score was calculated across subtests 2 and 3 (following (55)) due to the fact that over 90% of participants achieved the best possible performance for the first subtest. Three outliers were detected (n_{YA_CON} = 1, n_{OA_EXP} = 1, n_{OA_CON} = 1) for pre-training UFOV scores but only the data for the young adult participant was removed from subsequent analyses due to the expected heterogeneity of older adult UFOV performance.

Consistent with our past findings, there was a notable difference in the naturally-adopted mean speeds of older (M_{OA}±SD = 62.05±4.75) and younger adults (M_{YA}±SD = 68.09±4.43) during the first exposure to the Rural scenario. The 9.73% difference in means speeds between older and younger adults, while extremely similar to the 10.33-12% difference we previously described, also shows considerably decreased variability compared to those data. This may suggest that the auditory feedback we used to try and help participants regulate their speeds was effective at stabilizing speeds between individuals even if it could not entirely compensate for older adults' propensity to adopt naturally slower mean driving speeds.

In order to shed light on how the various driving measures were related with one another and with age, correlations were conducted both on pre-training and post-training data. Pearson partial correlations controlling for mean speed were computed to account for the fact that age still appeared to influence naturally-adopted mean driving speed despite the auditory feedback. Spearman correlations were performed instead for measures that did not follow a normal distribution.

To compare training task, UFOV, SSQ, and driving performance metrics between both groups, multiple linear mixed-effects models with repeated measures design were constructed including *Group* (i.e. Exp vs. Con) and *Age* (i.e. YA vs. OA) as categorical predictors and *Session* (i.e. Pre vs. Pos) as a within-subjects factor. *Group* was omitted as a factor when analyzing *2048* data due to the fact that the experimental group never performed the task. Generalized linear mixed models were used instead for variables not following a normal distribution. This approach is the most widely recommended method of analyzing pretest-posttest data—especially when group sizes are unbalanced (56,57). Finally, we analyzed SSQ change scores following the driving test in both pre-training and post-training sessions to rule out the possibility that one treatment group might have experienced more potentially confounding simulator sickness symptoms purely by chance.

3. Results

3.1 Pre-training partial correlation analysis

A graphical representation of the results of the pre-training partial correlation analysis on driving measures can be found in Figure 12. It was found that, after controlling for mean speed, 'Max Steer Change Rate' correlated positively with both 'Max Brake' [$r(31) = .35$, $p = .048$] and 'Steer Range' [$r(31) = .63$, $p < .001$]. Of these three measures, 'Max Brake' [$r(31) = .36$, $p = 0.038$] and 'Max Steer Change Rate' [$r(31) = .52$, $p = .002$) correlated positively with age. These finding are consistent with our previous research on these measures and are reflective of the compensatory actions taken by drivers in response to dangerous events (34). Older adults appeared to make more abrupt, less smooth driving maneuvers on both the steering wheel and the brake pedal in response to dangerous events—possibly reflecting a compensatory mechanism resulting from slowed information processing speed. A significant negative correlation between 'Distance at Max Brake' and 'Near Crashes' [$r(31) = -.37$, $p = .033$] also suggests that participants responding to events earlier were less likely to get into near crashes.

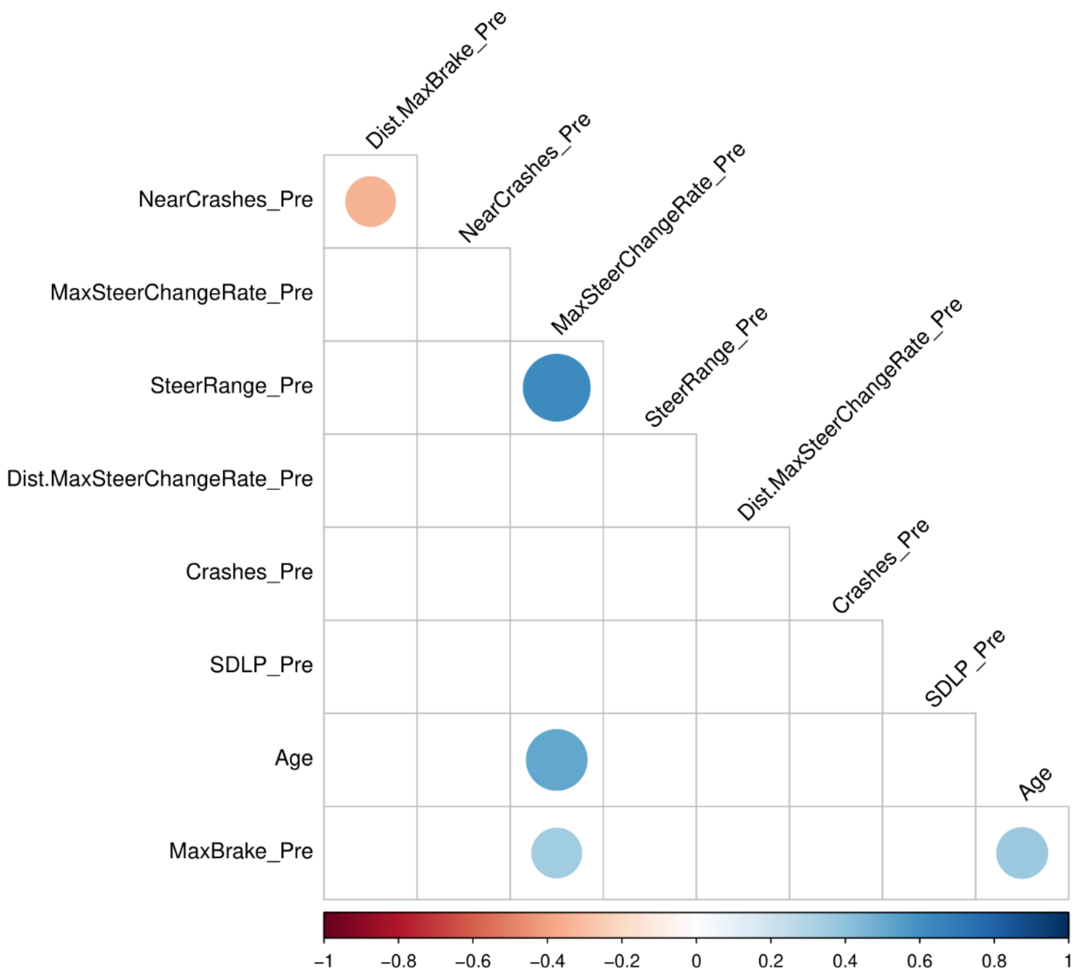

Figure 12. – Graphical representation of the pre-training partial correlation analysis controlling for mean speed (order via hierarchical clustering) generated in the R statistical environment (R Development Core Team, 2008). Only significant correlations ($p < .05$) appear on the figure. The size of each circle represents the magnitude of the correlation and the colour represents the direction.

Finally, a partial correlation was computed to study the relationship between baseline 3D-MOT and UFOV. Considering that performance on both measures is known to decrease with age, we elected to control for this variability inherent in our sample to better understand the association between the two measures. Consistent with other research (49), a moderate-strength negative correlation was detected [r(30) = -0.50, p = 0.004]. This further reinforces the idea 3D-MOT tests similar aspects of cognitive function as the UFOV but that performance on the task is partially subserved by other cognitive abilities.

3.2 Post-training analyses

3.2.a Partial correlations

The post-training partial correlation analysis can be found represented in Figure 13. Here, 'Max Brake' was positively correlated with 'Crashes' [r(31) = .50, p = .003], 'Steer Range' [r(31) = .60, p < .001] and continued to be correlated with 'Max Steer Change Rate' [r(31) = .43, p = .013] as well as Age [r(31) = .44, p = .01]. 'Crashes' were correlated with 'Near Crashes' [r(31) = .45, p = .008], 'Steer Range' [r(31) = .59, p < .001] and 'Max Steer Change Rate' [r(31) = .36, p = .039]. 'Max Steer Change Rate' was negatively correlated with 'Distance at Max Steer Change Rate' [r(31) = -.36, p = .041] and continued to be positively correlated with 'Steer Range' [r(31) = .48, p = .004]. Finally, 'Max Brake' correlated negatively with 'Distance at Max Brake' [r(31) = -.39, p = .024]. This last result suggests that individuals braking earlier were more likely to make controlled and deliberate stops (and vice versa), while the rest of these results paint a picture of individuals engaging in particularly extreme, last-minute driving maneuvers when faced with an imminent and unanticipated risk of collision. Such results are coherent with behavioural reports by Pacaux-Lemoine et al. of drivers forced into similar circumstances (58). Additionally, these individuals may have been more likely to get into near crashes as well; a finding that could reflect a certain profile of riskier driver or that may imply that individuals with higher crash rates responded to events later in general.

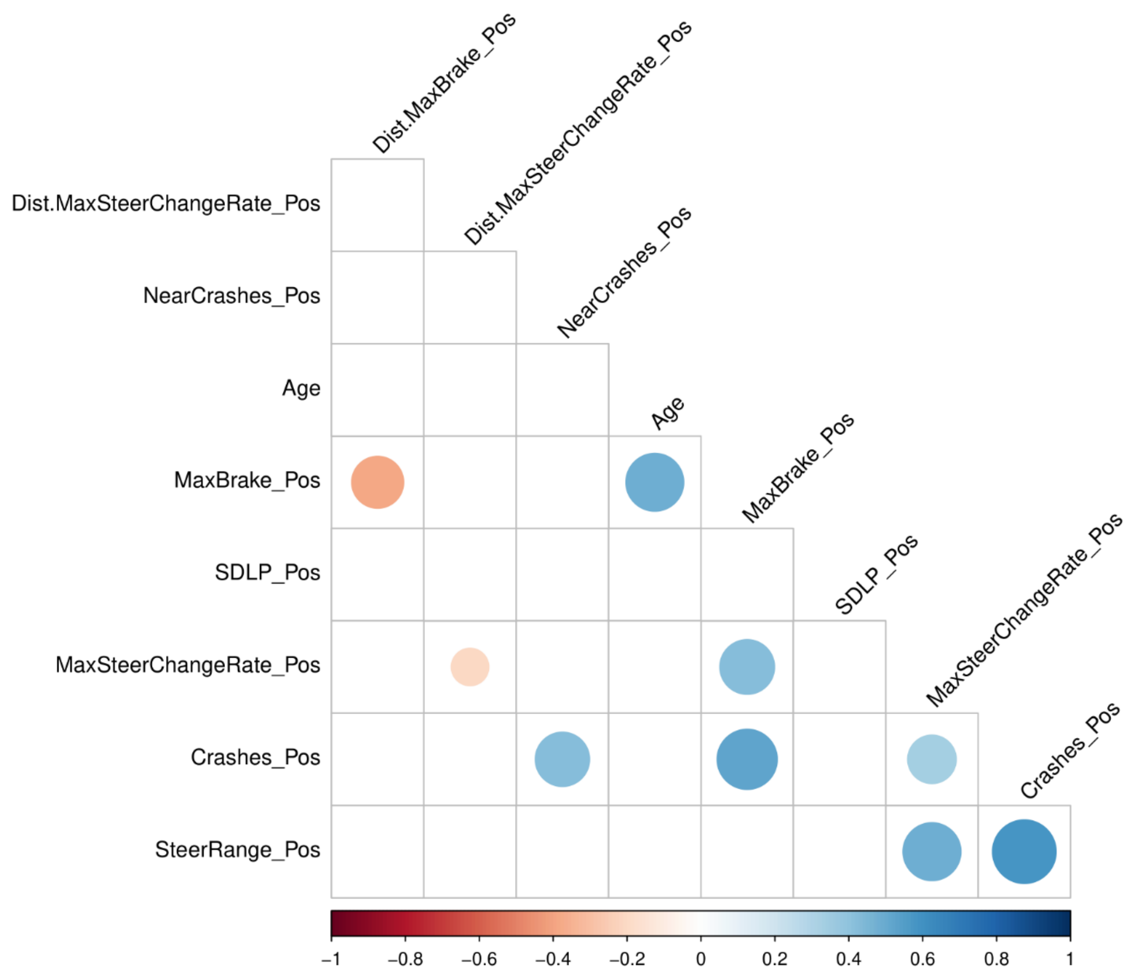

Figure 13. – Graphical representation of the post-training cluster partial correlation analysis controlling for mean speed**.** Only significant correlations (p < .05) appear on the figure. The size of each circle represents the magnitude of the correlation and the colour represents the direction.

3.2.b Mixed models & t-tests: *training tasks*

Next, we examined outcomes from the training tasks. As shown in Table 2, 3D-MOT performance showed the expected main effect of Age [$F(1,30) = 41.03$, $p < .001$, $\eta^2_p = .58$], an expected

Group*Session interaction [F(1,30) = 37.80), p < .001, η^2_p = .56], and a Group*Age*Session interaction [F(1,30) = 11.23), p = .002, η^2_p = .27] driven by the fact that the young adults in the control group (but not older adults) also demonstrated some improvement on the task (see Figure 6). Only a significant main effect of session (and no expected Group*Session interaction) was found for perceptual discrimination scores [F(1,28) = 5.36, p = 0.03, η^2_p = .16]. Finally, a main effect of Session was observed for *2048* [F(1,4) = -23.92, p = .008, η^2_p = .71], signifying that participants in the active control group improved at the task. The lack of a significant main effect of Age or an Age*Session interaction suggests that older and younger adults did not differ in terms of their baseline performance or improvement on the task.

Table 9. – Summary of the mixed model analyses for training tasks.

Measure	**Group (1)**	**Age (2)**	**Session (3)**	**1*2**	**1*3**	**2*3**	**1*2*3**	**R^2M**	**R^2C**
3D-MOT	.448	**< .001**	**< .001**	0.29	**< .001**	.72	**.002**	.63	.91
Perceptual discrimination	.98	.70	**.03**	.36	.71	.65	.16	.11	.24
2048	N.A.	.89	**.008**	N.A	N.A.	.69	N.A	.51	.62

Linear mixed models with Group (Exp vs. Con), Age (YA vs. OA), and Session (Pre vs. Pos) as factors were constructed to investigate differences in training task performance. Each main effect is named and assigned a number. Interactions between factors are indicated by these numbers. The resulting p-values are provided and bolded when significant. The final two columns represent the marginal (R^2M) and conditional (R^2C) R-squared values for each model. Note that the *Group* factor was omitted from analyses involving *2048* as the experimental group never performed the task.

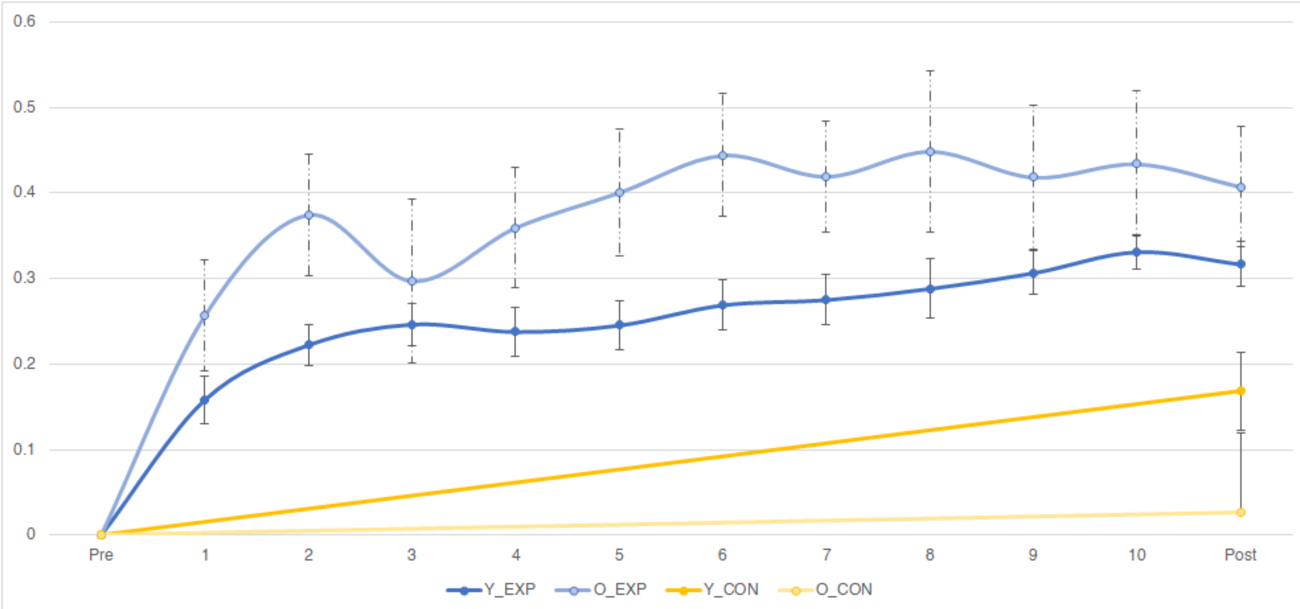

Figure 14. – Normalized learning curves (session scores – initial score) with group means and standard error bars for 3D-MOT log-transformed scores. Note the appearance of a plateau around session 6 for the older adult experimental group (O_EXP) compared to the younger adult experimental group (Y_EXP).

3.2.c Mixed models: *outcome measures*

Pre- and post-training mean outcome measure and training task data can be found in Table 10. Mixed models were constructed to investigate whether either training protocol transferred to relevant driving measures or UFOV ability and whether age had any influence. Additionally, a mixed model was constructed to investigate whether simulator sickness varied between treatment and/or age groups.

Consistent with the known propensity of older adults to experience more simulator sickness (59), a trend for a significant main effect of Age was detected for SSQ change scores [$F(1,30) = 3.70$, $p = .06$, $\eta^2_p = .11$] as shown in Table 11. Otherwise, no potentially biasing group or interaction effects were noted.

Table 10. – Descriptive statistics of pre-training and post-training measures.

	EXP			CON		
Measure	**Pre**	**Post**	**Δ**	**Pre**	**Post**	**Δ**
3D-MOT A,S,G*S,G*A*S	-0.02±0.14 -0.57±0.26	0.28±0.10 -0.09±0.13	+0.30 +0.48	-0.07±0.22 -0.32±0.27	0.10±0.13 -0.30±0.28	+0.17 +0.02
Perceptual discrimination S	.022±0.01 .026±0.01	.023±0.01 .019±0.01	+.001 -.007	.020±0.00 .026±0.01	.017±0.01 .022±0.01	-.003 -.004
2048 S	N.A. N.A.	N.A. N.A.	N.A. N.A.	2609.2±529.8 1221.1±797.1	5597.6±2175.6 5760±3020.7	+2988.4 +4538.9
UFOV A	75.35±28.08 255.76±89.07	57.09±24.01 220.79±85.13	-18.26 -34.97	90.12±28.80 224.56±162.71	85.91±18.34 231.27±242.70	-4.21 +6.71
Crash	0.80±0.63 1.14±0.69	0.40±0.52 0.57±0.53	-0.40 -0.57	0.70±0.67 0.71±0.49	0.60±0.52 0.71±0.76	-0.10 N.D.
Near Crash	0.80±0.79 0.71±0.95	0.40±0.7 0.71±0.76	-0.40 N.D.	0.50±0.71 1.0±1.0	0.80±0.92 0.43±0.53	+0.30 -0.57
Mean Speed A	68.24±4.18 59.63±2.12	69.17±4.54 61.12±1.57	+0.93 +1.49	67.94±5.53 64.48±5.53	69.08±3.5 66.35±6.61	+1.14 +1.87
SDLP G*A*S	0.28±0.05 0.27±0.03	0.29±0.04 0.29±0.05	+0.01 +0.02	0.28+0.05 0.31±0.03	0.30±0.06 0.29±0.05	+0.02 -0.02
Max Brake A,S	0.64±0.10 0.67±0.11	0.49±0.15 0.57±0.18	-0.15 -0.10	0.65±0.15 0.71±0.12	0.51±0.12 0.70±0.15	-0.14 -0.07
Dist. at Max Brake	41.63±9.98 43.94±19.93	49.27±7.79 46.57±14.05	+7.64 +2.63	42.76±13.71 44.71±9.95	43.27±9.74 42.67±10.66	+0.51 -2.04
Max Steer Change Rate A	293.28±46.09 363.67±44.65	314.51±73.55 315.15±36.24	+21.23 -48.52	293.34±50.10 334.71±59.24	322.80±67.24 358.24±50.06	+29.46 +23.29
Dist. at Max Steer Change Rate G*A*S	35.79±7.93 27.40±11.06	36.71±12.17 32.28±12.18	+0.92 +4.88	26.70±10.01 32.32±12.80	32.61±8.45 24.17±8.59	+5.91 -8.15
Steer Range	66.04±10.78 71.76±11.59	72.94±10.28 68.23±10.55	+6.9 -3.53	68.97±10.19 74.55±12.45	75.93±17.75 76.63±10.64	+6.96 +2.08
SSQ A	13.46±6.76 19.23±9.32	7.85±4.71 29.92±11.93	-5.61 +10.69	20.20±7.73 40.61±13.79	14.59±7.34 25.11±18.37	-5.61 -15.5

Means and standard deviations are provided for both training groups (EXP vs. CON) and both age groups (OA below YA in each cell) in their original units. Additionally, the difference (Δ) between pre- and post-training values are provided (N.D. = no difference). Finally, superscript letters for each factor (G = Group, A = Age, S = Session) are provided next to specific measure names to indicate when a significant main effect and/or interaction was detected for that measure.

Table 11. – Summary of the mixed model analyses for driving data.

Measure	Group (1)	Age (2)	Session (3)	1*2	1*3	2*3	1*2*3	R^2M	R^2C
UFOV	.87	**< .001**	.18	.65	.14	.88	.46	.37	.92
Crash	.98	.45	.20	.67	.20	.67	.31	.08	.08
Near Crash	.97	.67	.39	.75	.80	.62	.11	.10	.10
SDLP	.36	.84	.10	.74	.59	.21	**.04**	.06	.73
Max Brake	.22	**.03**	**< .001**	.35	.34	.08	.41	.26	.58
Dist. at Max Brake	.61	.95	.19	.91	.08	.26	.71	.04	.71
Max Steer Change Rate	.73	**.03**	.57	.93	.08	.10	.16	.16	.45
Dist. at Max Steer Change Rate	.21	.23	.68	.44	.35	.24	**.04**	.13	.47
Steer Range	.16	.55	.30	.66	.64	.21	.65	.08	.08
Mean Speed	.07	**< .001**	.12	**.05**	.86	.71	.96	.37	.60
SSQ	.33	.06	.53	.92	.30	.80	.30	.10	.28

Linear mixed models with Group (Exp vs. Con), Age (YA vs. OA), and Session (Pre vs. Pos) as factors were constructed to investigate differences in training task performance, UFOV, driving performance, and simulator sickness symptoms (SSQ). Generalized linear models were used instead in cases where variables did not follow a normal distribution. Each factor is named and assigned a number. Interactions between factors are indicated by these numbers. The resulting p-values are provided and bolded when significant. The final two columns represent the marginal (R^2M) and conditional (R^2C) R-squared values for each model.

No significant transfer to UFOV was detected. Both young and older adults in the experimental treatment group exhibited greater improvement in post-training performance on the task relative to controls ($\Delta YA\_EXP = -18.26$ & $\Delta OA\_EXP = -34.97$ vs. $\Delta YA\_CON = -4.21$ & $\Delta OA\_CON = +6.71$). While the improvement in young adults alone has been previously demonstrated to be statistically significant (40), older adults exhibited far greater variability in UFOV outcomes.

Indeed, the increase in mean UFOV detection speed threshold observed only in the older adult control group was primarily attributable to a single outlier who exhibited a substantially worsened score at post-training. Winsorization of UFOV scores in both of the previously identified older adult outliers equalizes the variability between the two older adult groups (SE_{OA} = 19.1 vs. 19.1) and reveals that the older adults in the experimental group had worse baseline UFOV scores compared to their control counterparts (M_{OA} = 236.8 vs. 172.8). Including these modified values in the linear model resulted in a trend toward a significant Group*Age interaction (p = .05) primarily driven by these random baseline differences in the context of a small older adult sample size. Older adults in the experimental group still exhibited a greater improvement in their UFOV scores compared to control subjects, but the magnitude of this difference was so small as to be practically nonexistent—especially when keeping in mind their lower starting point (Δ_{OA} = -16.0 vs. -10.9).

A main effect of Age was found for 'Max Brake' [$F(1,30) = 5.02$, $p = .03$, $\eta^2_p = .14$]. This result is attributable to an overall tendency for older adults to brake harder that was further emphasized by a sharper decrease in the maximum amount of braking applied by both experimental and active control younger adults (-0.15 & -0.14 respectively) compared to older adults (-0.10 & -0.01) during the post-training driving events. Interestingly, this difference was clearly strongest between young adults and the active control older adults in particular, but the difference was not great enough to evince a significant interaction. The significant main effect of Session for 'Max Brake' [$F(1,30) = 15.76$, $p < 0.001$, $\eta^2_p = .34$] is also explained by this pattern of results, suggesting that participants were likely more familiar with piloting the driving simulator at the second session and may also be related to beginning brake maneuvers earlier. The main effect of Age on 'Max Steer Change Rate' [$F(1,30) = 5.38$, $p = .03$, $\eta^2_p = .15$] is further indicative of the more abrupt actions taken by older adults when faced with dangerous events. Both of these results are consistent with correlations between age and these measures found for the Rural scenario in our previous study (34). While older adults adopted a mean speed slightly closer to their younger counterparts post-training, the model confirmed that there was still a strong main effect of age group on 'Mean Speed' [$F(1,30) = 20.37$, $p < .001$, $\eta^2_p = .40$]. A Group*Age interaction was found for this measure [F(1,30) = 4.28, p = .05, η2p = .12] and is attributable to a tendency for older adults in the control group to drive slightly faster than their counterparts in the experimental group (MEXPOA = 60.4 vs. MCONOA = 65.4). Possibly related to this was the presence of a significant 3-way interaction for 'Distance at Max Steer Change Rate' [F(1,30) = 4.52, p = .04, η2p = .13] where it was found that only older adults in the control group exhibited a decrease in this measure (i.e. later responding) (ΔEXPYA = +0.92, ΔEXPOA = +4.88, ΔCONOA = +5.91 vs. ΔCONOA = -8.15) as well as a 3-way interaction for 'SDLP' [F(1,30) = 4.50, p = .04, η2p = .13] where the same pattern was observed (ΔEXPYA = +0.01, ΔEXPOA = +0.02, ΔCONOA = +0.02 vs. ΔCONOA = -0.02).

Two interesting trends were also noted and are worthy of exploration considering the study's limited statistical power. First, a trend for a Group*Session interaction for 'Max Steer Change Rate' [F(1,30) = 3.24, p = .08, η2p = .10]. This is likely explained by the decrease observed for older adults in the experimental group at post-training (ΔEXPOA = -48.52) that was not observed for any other subgroup. Such a result may be related to increases in their 'Distance at Max Steer Change Rate' (ΔEXPOA = +4.88) and 'Distance at Max Brake' (ΔEXPOA = +2.63), possibly reflecting the fact that their slower mean speed would have allowed them to respond slightly earlier. Finally, a trend for a Group*Session interaction was found for 'Distance at Max Brake' [F(1,30) = 3.23, p = .08, η2p = .10].

When comparing means of the two training groups (MEXP±SE = 47.92±2.99 vs. MCON±SE = 43.0±2.99), it appears that the group trained with 3D-MOT completed their braking maneuvers slightly earlier when faced with dangerous situations. While the lack of a significant 3-way interaction would suggest that this improvement wasn't restricted to either young adults or older adults, the smaller difference and considerably greater variability in older adult post-training 'Distance at Max Brake' (shown in Figure 7) implies that the effect was less widespread in that age group. It also suggests that this difference was not simply related to the slower mean driving speed observed for older adults in the experimental group. This finding is again consistent with speculation that the training paradigm employed in this study may have been less broadly successful in the older adult experimental group.

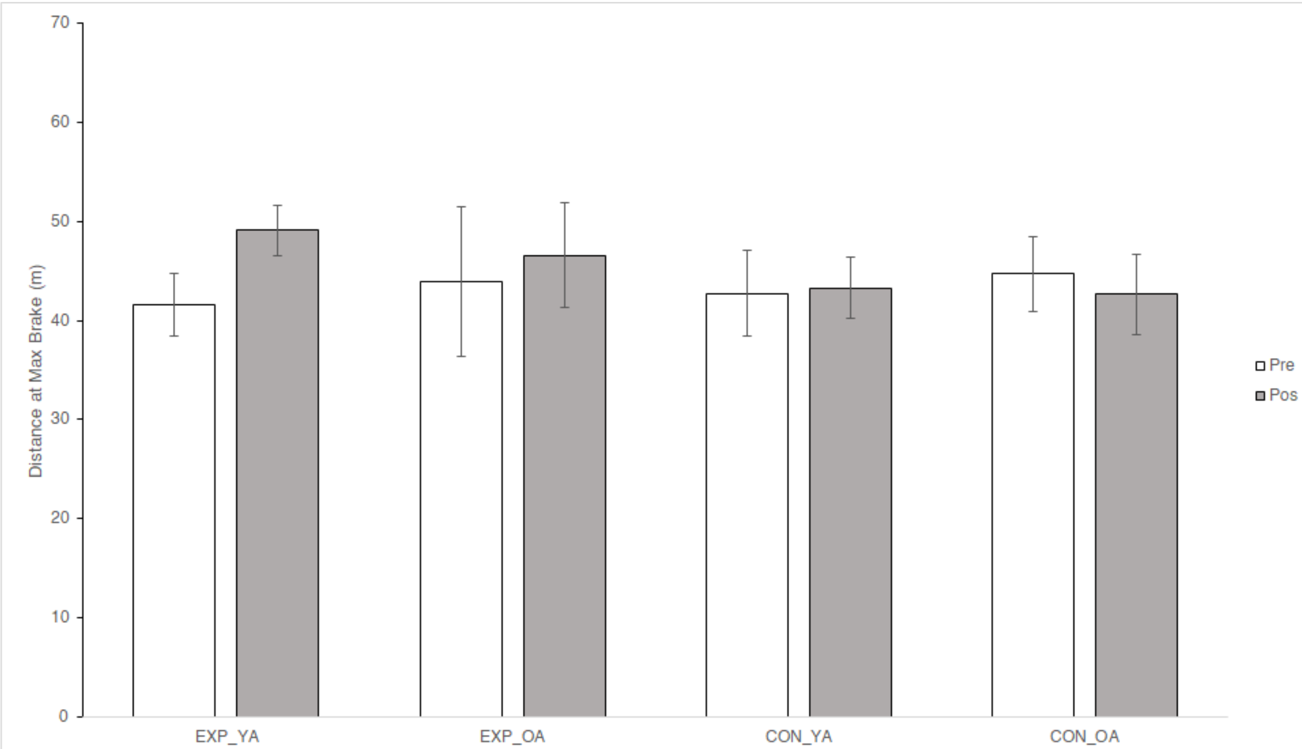

Figure 15. – Pre- and post-training mean values for Distance at Max Brake separated by training and age group. Error bars represent standard error of the mean (SEM).

4. Discussion

The main purpose of this study was to assess the feasibility of measuring changes in simulated driving performance following a 3D-MOT training protocol. Additionally, we also investigated whether the success of the protocol would vary as a function of age.

4.1 Training tasks

As expected, the experimental group showed significant improvement in 3D-MOT tracking speed thresholds as compared to the active control group. One interesting result to highlight is that of the improvement seen in the young adult active control group's tracking thresholds even after only a baseline assessment (see Figure 6). This result mirrors findings from Parsons et al. (38) who also observed improvement in their young adult control group from pre- to post-testing session that was comparable to the learning exhibited by the experimental group at their first training session (i.e., their second exposure to 3D-MOT) and shows that learning of the task lasts at least five weeks. Notably, this learning did not appear to translate into any measurable transfer effect on the driving metrics. This is consistent with results from the ACTIVE study using UFOV training and meta-analysis of cognitive training programs (60) suggesting that at least 10 sessions of perceptual-cognitive training may be required to measure transfer over and beyond practice effects (55). An unexpected related finding was the observation that older adults in the active control group did not seem to maintain much, if any, learning by comparison to their younger control counterparts. This difference in the durability of this learning was strong enough to produce a statistically significant 3-way interaction for 3D-MOT scores and suggests that there is still much to be learned about how ageing affects consolidation of cognitive training and the optimal training protocols for different age groups.

Despite faster initial improvement, older adults in the experimental group appeared to demonstrate a plateau after their sixth training session and their thresholds also demonstrated much greater variability at all training sessions. This finding may be explained by our decision to use four targets during the 3D-MOT training task. Previous 3D-MOT research conducted with older and younger adults has instead often resorted to using only three targets. Legault et al. (61) showed the inverse—that is, a plateau for younger adults but not older adults—using this paradigm. The logic of choosing three as opposed to four targets is that older adults often exhibit degraded perceptual-cognitive ability that, in many cases, renders tracking four targets disproportionately more difficult relative to their younger counterparts. We elected to use four targets as we worried that the aforementioned plateauing shown in younger adults when trained with three targets might interfere with possible transfer here. Additionally, we wanted to keep the training parameters identical between subjects for ease of comparison. Instead, we may have inadvertently limited the learning potential of the older adult training group. Coupled with the small sample size of the present study and the limited number and duration of training sessions, these factors may have reduced our ability to detect even the type of mid-level transfer that is routinely showed in cognitive training studies. Future work that permits more granular stratification of older adult participants contingent on factors such as baseline performance may help shed light on such questions.

Similar differential transfer effects between younger and older adults have been reported in a training study by Dahlin et al. (62). Their results further demonstrated that initial age-related changes in the neural substrate solicited for performing the training task resulted in less overlap of brain activation with the untrained task for older adults. It is possible that similar age-related differences in neural activation could exist for the 3D-MOT task and, additionally, it is reasonable to assume that such differences would be magnified as the task's complexity is increased via greater tracking load and speedConsidering how the adaptive nature of the 3D-MOT task is a key feature of its design, future training studies comparing younger and older adult outcomes should consider this trade-off carefully during experiment conceptualization. Future work could also benefit by following the recommendation of Lustig et al. (63) to use neuroimaging data in order to provide a clearer mechanistic account of transfer following cognitive training.

The presence of a main effect of Session but a lack of a significant Group*Session interaction for the perceptual learning task suggests that both groups demonstrated rapid improvement at the task. That the experimental group also improved at the task is not inconsistent with the established literature on perceptual learning, which typically shows that it can occur rapidly (64). The lack of an interaction is somewhat surprising, however, considering the great difference in exposure to the task by the post-training test. It is possible that demonstrating stronger group-specific perceptual learning on such a task could require either more trials than was conducted here or that the study lacked adequate power to detect small additional differences following training. It is also possible that more obvious learning would have been demonstrated following a longer training duration. This is equally true for possible transfer to the driving task in the experimental group. Indeed, a recent meta-analysis suggests that cognitive training protocols using 24 or more sessions across 8 weeks produce significantly stronger effects than those with fewer sessions (60). The fact that we were unable to demonstrate any age-related differences on the task is not particularly surprising. In fact, it has been suggested that the type of low-level processing required for perception of simple first-order stimuli may not be complex enough for age-related deficits to be consistently observed (65). Finally, the learning effect demonstrated for *2048* suggests that active control participants were engaged in their training phase sessions.

4.2 Driving measures

Analyses on pre-training data replicated many of our past findings but not all of them. In particular, age was not positively correlated with 'SDLP' or 'Crash' and neither measure was significantly greater in the older adult group as was previously observed. This may either reflect factors unique to our sample or simply that the present study lacked adequate power to observe the same patterns. Indeed, while a major limitation of this study is the small sample size, it was especially limited for older adults who are already characterized by their greater heterogeneity in health and intervention outcomes (66). What does appear to be consistent, however, is that age was associated with more extreme braking and steering maneuvers. This was true even while older adults compensated for decreased reaction time by adopting slower mean driving speeds. These results are in line with and further reinforce the established literature on maladaptive or compensatory older adult driving behaviours (67-72). Finally, we showed that unobtrusive auditory feedback was capable of reducing some of the difference in naturally-adopted mean speed between younger and older adults but could not eliminate it entirely.

As far as transfer to driving performance is concerned, the present results offer some evidence that 3D-MOT training may increase the distance at which drivers respond to dangerous events. Considering that such training has been shown to improve visual attention and speed-of-processing (38,40,43,73), this result could be the result of better distribution of attention or more efficient processing of the dynamic visual scene. Cuenen et al. (74) have highlighted attentional function as an important predictor of improved detection and reaction times during driving. Additionally, speed of visual information processing has for a long time been associated with driving safety and longitudinal driving outcomes through the body of UFOV research (25,30,55,75). Mackenzie & Harris (76) also recently demonstrated important links between driving safety, attentional function as measured by MOT performance, and visual speed of processing by way of differences in eye movement behaviours. Interestingly, our result has parallels with findings from Roenker et al. (31) who showed that UFOV training improved drivers' reaction times and suggested that this could translate to improved stopping times. Somewhat relatedly, studies with young action video gamers have also demonstrated improved perceptual speed-of-processing and reaction times observed across various tasks divorced from the context of gaming (77). However, considering the limitations of the current study, a replication with larger sample sizes would help assuage reasonable doubts about this interpretation.

Though an average relative gain of only about five metres at the point of maximum braking seems modest, one should keep in mind that a driving speed of 70km/h translates to roughly 19m/s and 50km/h translates to roughly 14m/s. Thus, reacting and completing a braking maneuver even this little bit earlier could potentially help avoid some worst-case scenarios by allowing the vehicle more time to decelerate. While no associated difference in 'Crash' or 'Near Crash' was detected, this may simply be due to the fact that these outcomes were extremely rare in the first place coupled with the relatively low power of the study. Both before and after training, the mean number of crashes ($M_{Pre} = 0.84$ vs. $M_{Pos} = 0.6$) and near crashes ($M_{Pre} = 0.53$ vs. $M_{Pos} = 0.59$) for all participants was less than one. This implies that most drivers were capable of responding to all the dangerous events in time, rendering it difficult to demonstrate significant change on these measures. Nevertheless, both the younger and older adult experimental group demonstrated reductions in their mean number of crashes where the control group either did not or showed a much smaller difference. Interpreting this result requires caution, however, due the lack of statistical significance.

Additionally, post-training correlations between driving measures seem to indicate that drivers with greater 'Distance at Max Brake' also had lower 'Max Brake' and, additionally, that increased 'Max Brake' was associated with 'Crashes'. This—alongside the pattern of correlations between 'Max Brake', 'Crashes' and other measures of uncontrolled driving—helps reinforce the interpretation that the experimental group exhibited more deliberate and controlled stops.

Conclusion

To conclude, this study offers preliminary evidence that 3D-MOT training improves a specific measure of driving performance. While we and other researchers have previously demonstrated associations between 3D-MOT and driving ability (34,35), to our knowledge this is the first study suggesting it may be possible to measure transfer to driving. These results should be interpreted with some caution: sample size concerns, the interpretation of trends, and the simulated nature of the task limit the generalizability of this study. Additionally, p-values were not adjusted for multiple outcome measures given the exploratory nature of the study. As such, the current study is best viewed as a feasibility study as described by the taxonomy from Green et al (78).

The results presented here, while not an unambiguous demonstration of transfer to driving, are a justification for continued research into whether 3D-MOT training improves driving safety. Despite all their advantages, future research of this type should move beyond contrived driving simulator scenarios to truly demonstrate real-world benefits of such training. Looking ahead, such studies could investigate longitudinal driving outcomes following 3D-MOT baseline measures and training much like the ACTIVE study already has for UFOV training.

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5. Discussion

5.1 Experimental objectives

The research presented in this thesis was conducted with the goal of demonstrating the utility of using 3D-MOT ability as a predictor of driving performance and to investigate whether training tracking ability would result in any beneficial transfer to driving or to a cognitive measure previously implicated in driving safety i.e., the UFOV.

5.1.1 Experiment 1

The first experiment had two main objectives. The first of these was to develop and validate a novel driving simulator methodology for assessing driving performance in different driver age groups. The second was to determine whether baseline 3D-MOT ability is associated with or even predictive of any aspects of driving performance. The first of the peer-reviewed articles above demonstrates that this goal was successfully achieved, laying the foundation for the two articles that follow.

Even though driving simulators have seen use since as early as 1934 (1), their use in research contexts has become truly widespread in the last few decades due to improvements in their availability and realism. Researchers working with flight and driving simulators have recently argued that for simulators to be used effectively as scientific instruments, the specific simulator model, performance metrics, and scenarios employed must be evaluated for validity and acceptability in each population of interest (2–5).

In this study, a large sample of drivers ranging in age and experience were tested on three custom-designed driving scenarios meant to invoke varying levels of mental workload. A number of novel and well-established driving performance metrics were evaluated for significant intercorrelations and, based on these results, several non-redundant and useful new metrics were established to characterize driving performance in subsequent analyses. Performance on each of the three scenarios was then compared between the different age and experience groups and the suitability of each scenario was evaluated. It was determined that the moderate mental workload Rural scenario was the most appropriate for use in studies comparing older and younger adult driving performance, as it was most able to elicit naturalistic driving behaviour in each of the groups tested.

The next step after establishing the ideal scenario and performance metrics to study was to determine whether a relationship existed between variability on these metrics and cognitive function as assessed by 3D-MOT. Correlation analysis revealed that 3D-MOT performance was indeed associated with adverse driving outcomes such as crashes as well as measures of uncontrolled driving performance such as standard deviation of lateral position (SDLP) and naturally-adopted mean driving speed. A subsequent multiple linear regression analysis demonstrated that diminished 3D-MOT performance was the best predictor of crashes compared to age and mean driving speed and that it was also a better predictor of self-restriction of driving speed compared to age.

These results help establish the validity of a specific, new driving simulator research methodology and confirm that 3D-MOT—an integrative measure of dynamic visual attention—can be used to predict simulated driving performance in a manner similar to UFOV. More generally, the study contributed several novel insights to the burgeoning field of driving safety research using high-fidelity driving simulators.

5.1.2 Experiment 2

Once a methodology sensitive enough to distinguish individual differences in driving ability was established—and upon determining that 3D-MOT performance predicts aspects of driving performance—the next logical question to pose was whether training 3D-MOT ability can improve measures of driving performance. Related to this is a multitude of questions about why such training might transfer to driving. This is a more than fair line of questioning: driving is a highly complex behaviour and far-transfer of cognitive training has only rarely been shown for 3D-MOT training (6) and cognitive training more generally (7).

While it is possible that there are features unique to MOT that overlap with skills needed to drive safely (e.g., efficiently allocating and dividing attention in a highly dynamic visual scene), the evidence that UFOV ability predicts (8) and seemingly transfers to components of driving performance (9) suggests that even lower-level aspects of cognition like visual information processing speed might also contribute. 3D-MOT is claimed to be an integrative test of numerous cognitive domains, including those solicited by the UFOV task such as speed-of-processing with attentional demands (10). Thus, there is also a rationale for trying to determine whether 3D-MOT training transfers to the cognitive domains underlying UFOV ability. If it does, this might help clarify the mechanisms by which far-transfer to driving could occur.

The results of this experiment have thus far generated two articles: articles two and three of the present doctoral thesis. The first of these two articles—prepared before the global COVID-19 pandemic delayed and ultimately curtailed continued recruitment of older adults—demonstrated mid-level transfer of 3D-MOT training to UFOV performance in young adults relative to active control subjects of the same age. In doing so, it demonstrates that these two tasks are subserved at least in part by the same cognitive mechanisms and reinforces the notion that these can be trainable. The second of these two articles extended this analysis by seeming to show differential, possibly contradictory effects of training in the older adult participants. A possible resolution to this contradiction might lie in the pattern established by the study's other findings.

The third article in this thesis also presents evidence for potential far-transfer of 3D-MOT training to simulated driving performance. This result is interesting considering the relative paucity of experiments that have thus far demonstrated far transfer of cognitive training and the skepticism expressed by some researchers regarding its possibility (6,7,11).

The experimental group exhibited a post-training decrease in the distance at which they applied their maximum amount of force to the brake pedal during a dangerous event. This measure was also negatively correlated with the maximum amount of force participants ultimately put on the brake pedal. This suggests that participants beginning their stops earlier were able to do so in a more controlled manner and that the experimental group more consistently exhibited this pattern of behaviour.

The experimental group also exhibited a greater decrease in the number of crashes they experienced post-training compared to the control group, although this difference did not reach statistical significance. These findings suggest that the experimental group were either noticing potential dangers earlier or were reacting faster once they were noticed. Thus, they could avoid making more abrupt, uncontrolled driving maneuvers. The finding that younger adults also significantly improved their UFOV performance suggests that the training may have successfully improved the efficiency of their visual processing under attentionally-demanding conditions. This seems to have produced a faster complex reaction to sudden danger.

5.2 Limitations

The two studies presented here each have their own respective limitations. The main limitation highlighted in the first study was related to the decision to allow participants to control their own driving speed. While this resulted in a more realistic driving test and more authentic driving behaviour, it also meant that participants could effectively give themselves more time to react to dangerous events by adopting slower driving speeds. Thus, it is possible that the first study was ultimately limited in its ability to detect how variation in the cognitive abilities measured by 3D-MOT ultimately affects driving safety. Clearly there is no “one-size-fits-all” solution for this issue as driving study methodologies that restrict participants’ control over vehicle speed carry their own set of trade-offs.

The second study attempted to address this by instructing participants to follow speed limits as closely as possible while offering auditory feedback to unobtrusively facilitate this process. This was only partially effective as ANOVA still revealed a significant main effect of age on mean driving speeds even if the relative difference between young and older adults was smaller compared to the first study. Interestingly, older adults still demonstrated their previously observed tendency to brake harder in response to dangerous events despite their generally slower driving entering into events. Additionally, even though their slower driving style should have provided them more time to assess each driving situation and react accordingly, they did not differ in terms of the distance at which they ultimately applied their maximum braking force. Thus, this more extreme braking style may represent another compensatory behaviour resulting from slowed processing speed.

Another potential limitation of both studies has to do with the differential effects of simulator sickness. While only a small number of participants reported significant discomfort in the second study, there was a clear trend for older adults to experience worse symptoms and these data were not collected during the first study. Additionally, while it was indeed the case that the majority of subjects reported considerably fewer symptoms following their post-training test, a select few—one older and one younger adult in the control group as well as one older adult in the experimental group—actually exhibited the opposite trend. This pattern of results seems to suggest that a small number of individuals exhibited an unexpected sensitization to SSQ symptoms after the first exposure rather than an adaptation effect. It is unclear how or if this may have impacted their driving performance. The lack of a treatment group*age group interaction suggests that simulator sickness wasn't more pronounced in one older adult group or another, however.

In general, participants that completed the study reported light symptoms at worst. However, it is unclear how the effects of simulator sickness may have biased the composition of the final sample or affected the driving metric results measured for older adult drivers in both treatment groups. While at least one study conducted by other researchers excluded data from all participants reporting any symptoms of simulator sickness (1), such a stringent criterion was unfortunately not an option for this study as it would have effectively reduced the sample size to a total of only six participants if both sessions were considered.

Simulator sickness aside, another possible limitation of these studies has to do with the inherent differences between the simulator and real-world driving platforms. While there is good evidence demonstrating that training drivers with simulators transfers to real-world driving performance (2), a review by Mullen et al. rightfully points out that simulators only approximate on-road driving behaviour (3). Mathias & Lucas further point out that using simulators to assess driving performance may disadvantage older drivers due to the likelihood that they are less experienced with computerized stimuli and 2-dimensional reconstructions of 3-dimensional stimuli (4).

Other researchers have occasionally addressed these issues through validation studies that not only compare simulated driving performance metrics to established patterns of driving behaviour, but also to those same performance metrics measured during additional on-road driving tests designed to mirror the simulation (5,6). Even disregarding questions of technical feasibility, the fact that outcomes of interest were complex behavioural responses to imminent dangers means that simulation was likely the only ethical way to conduct this research. While the results of the first study echo those found by other researchers able to compare driving performance on both platforms against each other (1), a recent review of the driving simulator validity literature highlights that only around half of validation studies demonstrate absolute or relative validity (7)—a finding that casts some doubt on the generalizability of results from many simulator studies.

A major strength of the second study compared to many earlier cognitive training studies involving different tasks lies in the decision to use an active control group for comparisons. This decision should be counterbalanced against the possible bias introduced by the challenging-to-avoid single-blind design of the study. While all participants were informed that they were recruited to test the possible benefits of a computerized cognitive training paradigm on driving performance, it is difficult to entirely rule out the possibility of demand characteristics somehow affecting participant behaviour. That said, participants were isolated from researchers during the driving test and all received identical instructions for outcome measure tasks regardless of group randomization. Thus, it is difficult to imagine how the single-blind design of the study could have impacted participants' braking behaviour.

The most obvious limitation of the second study was the small sample size—both in terms of study participants and in terms of the breadth of the driving behaviours sampled. Recruitment of older adults in particular proved challenging early on due to the substantial commitment posed by needing to travel for ten in-person training sessions as well as pre- and post-training sessions. The lengthy suspension of experiments involving human participants as a result of the COVID-19 pandemic and subsequently even greater hesitation of many older adults to participate once recruitment could resume ultimately forced an early termination of data acquisition. In combination with the characteristically greater variability of older adults (8), this limited the statistical power of the study and rendered it difficult to detect possible treatment and interaction effects.

Nonetheless, the study still demonstrated a change in driving behaviour across a relatively small number of participant reactions that was consistent with what would be predicted by an enhancement in cognitive abilities solicited by 3D-MOT and UFOV and shared with driving. While sample size is not generally regarded as influencing the risk of type 1 error, the use of multiple outcome measures can. This raises concerns about whether or not p-value adjustment should have been employed to reduce this risk; a widely held debate for studies in fields where conducting a massive amount of simultaneous hypothesis tests is not the norm (9,10). Even the most liberal commonly-used p-value adjustment would have rendered the main finding of the third article marginally significant at best. Thus, two reasonable minds may disagree whether the study ultimately did have enough statistical power considering how low α' values and, consequently, how stringent significance thresholds become with even fairly liberal adjustment for multiple outcome measures.

Considering the complex nature of driving as a behaviour, it is difficult to imagine quantifying it effectively with just a single outcome measure. While other researchers have addressed this problem using composite measures of a variety of distinct performance measures, doing so here would be challenging considering that the various metrics used in these studies needed to be understood in relation to one another to accurately describe the global behaviour. Considering the somewhat marginal significance of the main result for distance at maximum brake ($p = 0.041$), a skeptical reader might therefore choose to see this study as preliminary.

A final limitation of the study was the lack of a follow-up testing session to determine if any of the observed beneficial transfer of 3D-MOT training would endure. While a planned 3-month follow-up test was conducted for many of the subjects, attrition in addition to the pandemic resulted in a large number of participants missing this session. Considering that other research has called into question the lasting transfer of short-duration cognitive training (11), future analyses should examine the limited data that was collected or try to aggregate it with the results of another study to investigate the durability of 3D-MOT training benefits.

5.3 General discussion

The present studies offer evidence for successful, ecologically-relevant applications of 3D-MOT assessment and training. The first study reinforces the established literature demonstrating the importance of cognitive ability measures as predictors of driving performance. The second study adds to the limited evidence that training these abilities may enhance aspects of driving performance.

5.3.1 What is the real-world significance of these results?

This raises another question, however: how do reactions to a series of contrived dangerous situations correspond to average real-world driving? Situations with close parallels to those used in these two studies are unlikely to be very common in the real-world. While accidentology research is clear on the fact that slower processing speed and inefficient allocation of visual attention are real risk-factors while driving (22–24), it is abundantly clear that inexperience, risk-taking, driving under the influence, and distracted driving are also major factors and are likely more common collectively than surprise obstacles requiring sudden reactions. Indeed, experienced drivers are known to avoid putting themselves at-risk of needing to make drastic, last-minute maneuvers through their superior anticipation and hazard perception (25). This was evident to some extent in the second study where crashes during events-of-interest were relatively rare and completing braking maneuvers earlier did not ultimately translate to a statistically significant decrease in crash risk.

While improving the speed at which people complete their reaction to sudden dangers seems superficially beneficial, does such improvement matter if the average reaction was still sufficient to avoid collisions? This question strikes at the heart of what our expectations for the effects of cognitive training perhaps ought to be versus how the benefits of such training are frequently marketed. Driving is a complex task and it is probably unreasonable to assume that cognitive training would improve basic vehicle maneuvering capabilities, strategic driving behaviours honed through experience, alter younger driver behaviour in the social contexts where they are known to take greater risks, or somehow make dual-tasking while driving a wise decision. In other words, cognitive training is unlikely to make someone a better or safer driver in many of the most directly observable ways.

While individualized educational interventions geared at teaching drivers how to better avoid dangerous situations; avoid distracted driving; or self-regulate after sensitization to declining cognitive abilities could ultimately prove more effective at improving driver safety, computerized cognitive training is a low-cost and highly scalable solution at the population level. When it comes to older adults with declining functional abilities, sometimes it takes experiencing a potentially life-threatening situation before individuals or their family are willing to take steps to address the problem (26). As the population continues to get older, improving the methods with which we can detect at-risk drivers and intervene before these possibilities occur is a growing preoccupation for many adults who continue to perceive driving as a necessity (27).

Clearly it is best to never find oneself in a potentially life-threatening situation while driving. That said, there is certainly value in being better prepared for the possibility: assessing perceptual and cognitive abilities and subsequently training them might be one way to do so. While the present results don't demonstrate beyond all reasonable doubt that 3D-MOT training can, in fact, maintain or improve an individual's absolute risk behind the wheel, they offer a tantalizing hint at the possibility.

5.3.2 Are these results consistent with the literature?

It can be difficult to compare the results of this study to the results of similar studies considering the great variability in cognitive training and driving assessment methodologies: First, practically every study that has investigated transfer of cognitive training to driving performance has been performed with only older adults. Additionally, training programs, experimental tasks, and performance measures are rarely identical across different studies.

Cassavaugh & Kramer trained older adult participants with a battery of different cognitive training tasks—including one modelled after the UFOV—to solicit selective attention, visual working memory, compensatory vehicular control, and dual-task coordination (12). They studied performance on multiple simulated driving tasks including a car-following task, a visual working memory task, a monitoring task, and dual-task combinations meant to represent different components of driving.

In the car-following task, participants were required to maintain a constant following distance from a lead vehicle that would either brake or accelerate approximately every 20 seconds. The main outcomes of interest were reaction time on the accelerator pedal as well as root mean square (RMS) error of lane position and following distances. This task was occasionally paired with the next two tasks. In the visual working memory task, participants were required to remember information viewed while driving: specifically, they were required to press a button if the colour of a passing vehicle matched the colour of the last passing vehicle. Finally, the monitoring task asked participants to press a button when they detected appearances of moderately-difficult-to-detect targets superimposed randomly over the driving scene. Reaction time was the principal outcome of interest for these two secondary tasks.

Using regression-based analyses, they found that the improvement they measured in the attention and working memory training tasks explained additional variance over baseline driving and training task performance alone in their post-training driving performance measures. Specifically, they found that the models including training gains were better able to account for variability in performance of: lane position during the "following and monitoring" dual-task and accelerator pedal reaction time during both "following and monitoring" as well as "following and memory" dual-task conditions.

While the effects were small, they were statistically significant and seem to demonstrate transfer of training to driving performance. Interestingly, effects were only observed when trying to account for performance in dual-task conditions. This may suggest that their primary task was not challenging enough by itself to tax older adult cognitive functions such that individual differences in cognitive ability would manifest in decreased driving performance. The need for sufficient task complexity to reveal decline in perceptual and cognitive abilities of older adults has been previously highlighted and some have speculated it may reflect inefficiencies in restructured neural processing pathways meant to compensate for functional decline (13). It also motivated the investigation into the interplay between mental workload, driving performance and age that was a feature of this thesis' first study.

Another study conducted by Roenker et al. compared the effects of UFOV-like speed-of-processing training with traditional simulated driving training in older adult participants with poor baseline UFOV ability (14). They also included a low-risk reference control group that did not receive any training. The study included two different types of principal outcome measures: 1.

simple and complex reaction time and 2. an on-road driving evaluation along a predetermined urban/suburban route.

The reaction time tests were conducted within a driving simulator and required participants to make the correct responses as quickly as possible upon presentation of specific signals. For the simple reaction time test, participants merely needed to brake when presented with a specific signal and avoid braking in response to other signals. For the complex reaction time test, participants either had to brake, turn the steering wheel in a specified direction, or do nothing depending on the specific signals being displayed during each trial. The driving evaluation was conducted under the supervision of a professional driving instructor in the passenger seat and three independent raters sat in the back of the vehicle. All were blind to the training condition assigned to participants. Performance on over 400 complex driving behaviours was aggregated into 13 composite measures for analysis. Some of these included: gap selection, smoothness in acceleration and deceleration, proper use of signals, vehicle speed control relative to posted limits, etc.

The traditional driving training group exhibited improvements in proper signal usage and in proper selection of which lane to turn into at intersections. Both represent skills that are essentially subserved by semantic memory—that is to say, once the proper rules for signaling and turning are learned, practice isn't strictly necessary to integrate them into one's driving behaviour. Thus, it makes sense that driving training focusing in large part on these theoretical aspects of driving performance should produce improvements in at least these areas.

By comparison, the speed-of-processing trained group exhibited significantly improved performance in their complex reaction time as well as a significant decrease in the dangerous maneuvers composite. This composite represented the number of times the driving instructor needed to take control of the vehicle based on their perception of the participant making an overly risky driving maneuver and thus represented better performance in cognitively-demanding situations such as navigating visually cluttered intersections and selecting appropriate gaps to turn across oncoming traffic. Considering how many of the other composites primarily related to low-level driving skills that all participants were able to perform at near-perfect level—or else components of driving performance largely dependent on knowledge—it is not particularly surprising that cognitive training did not transfer to these areas.

Interestingly, the improvement the authors noted in complex reaction time corresponded to a potential decreased stopping distance of 6.7 metres—a result very much in line with the improvement observed in article 3 presented earlier. There, it was observed that the 3D-MOT training group exhibited an average improvement of approximately 5 metres in the distance at which they applied maximum pressure on the brake pedal relative to the active control group. Population differences aside, this similarity further reinforces the interpretation that 3D-MOT training improved the speed at which participants were able to process the dynamic visual scenes in which hazards were embedded and react accordingly.

In contrast to these two studies are the results of a final study using a methodology that most closely resembles the one used in article 3. Gaspar et al. compared the driving performance of a group of older adults trained using the CogniFit® Senior Driver program—a commercially-available assessment program that targets a wide range of cognitive abilities including reaction time and attention—versus an active control group that played card games on a computer (15). They used two simulated driving scenarios. Like the test used in article 3, the first of these was a hazard response task where participants drove through a straight, two-lane urban road with ambient traffic and pedestrians and were instructed to keep their speed as close to 35mph as possible. Participants received warning messages if their speed fell below or exceeded a 10mph range around this target. Reaction time to a series of pre-programmed, sudden hazardous events was the primary measure of interest.

The second scenario was a highway driving task where participants were instructed to merge onto a busy three lane highway and maintain a speed of 55mph. Cars ahead of the driver would occasionally slow down and cars behind the driver would occasionally speed up which would necessitate participants to either maintain steady-state following behaviour to maintain their speed as close to 55mph as possible behind a lead vehicle or else they would have to carefully change lanes to overtake slower vehicles. Here, the measures of interest were steady-state following distance and the safety margins that drivers maintained when merging to new lanes.

The study found no group differences in post-training reaction times, in following behaviour, or in the size of the safety margins drivers maintained while merging. The authors unfortunately did not report on driver mean speed for the hazard detection task so it is unclear how well their participants performed the secondary task of speed maintenance and whether or not their older drivers exhibited similar extreme speed self-regulation as discussed for the urban (city) scenario in article 1 above. It is also interesting to consider these results in light of the findings from article 1 suggesting that visually-cluttered urban scenarios may not be well-suited for eliciting realistic driving behaviour in older adults. The authors did not report any crash or other driving metric data and excluded trials that ended in a crash from their analyses.

The authors speculated that the difference in their results relative to the previously discussed Roenker et al. article may be explained by the fact that those researchers chose to only train participants that had been previously identified as having diminished processing speed. This suggestion echoes the compensation account of learning and transfer that posits that individuals already functioning at optimal levels have less room for improvement (16). By contrast, the magnification view instead argues that individuals starting at a higher level "should have more cognitive resources available to acquire, implement, and sharpen effortful cognitive strategies". It has also been suggested that interindividual differences in the effects of ageing on neuroplasticity might play a role (17) but diminished speed-of-processing may also be implicated (18).

There is support for both: the latter has been more often demonstrated in the context of studies on age-related differences in the effectiveness of mnemonic memory training techniques such as the method of loci (19) while the former has been demonstrated for executive control training (20). Some studies suggest that individuals with lower baseline working memory ability stand to gain more from training both in terms of learning and in terms of transfer relative to individuals with higher baselines (21,22). In truth, it is likely that many more factors are at play when it comes to interindividual differences in training results and transfer—an opinion shared by numerous researchers working in the field (20,23). Indeed, research has clearly demonstrated speed-of-processing training-related improvements in cognitively normal older adult reaction time (24) and even in young adult attentional resource allocation as measured by pupil diameter data (25).

These findings, the findings of Cassavaugh & Kramer, and the findings of this thesis, tend to suggest that the null result of Gaspar et al. should not be attributed to their sample not exhibiting sufficient cognitive decline. Instead, it is more likely that these results are explained by methodological choices or sample-specific factors that limited the study's ability to detect differences in reaction times. Or—more pessimistically—that the studies demonstrating far transfer have merely done so by chance.

5.3.3 Differential effects of training based on age

As previously discussed, the compensation account of learning suggests that older adults in the experimental group should perhaps have stood to gain more from 3D-MOT training given their lower baseline performance. While this was true initially, their learning functions exhibited signs of a plateau after approximately six training sessions such that younger adults began to catch up by the end of the training phase. This might indicate that older adults either required considerably more training to improve further or else that further improvement might have been impossible with the four-target training paradigm employed here. This differential learning outcome also seemed to extend to the degree of transfer observed in each age group: young adults drove the majority of the between-group difference measured in braking behaviour.

Does this result lend support to the magnification view of learning or is perhaps another factor at play? Surprisingly, very few 3D-MOT training studies have directly compared older adult and younger adult learning functions which renders it difficult to properly address this question. It has been established that older adults tend to struggle with tracking four targets simultaneously (26). Thus, at least one 3D-MOT training study comparing younger and older adults elected to require participants to track three targets instead of the more typical four (27).

This study found that under such conditions, older adults exhibited identical learning curves to younger adults but younger adult performance started considerably higher and their learning began to plateau by the end of the training period. By comparison, older adult learning had not plateaued by the end of the training period, which suggests that they could have improved further and possibly reached young adult levels of performance with sufficient practice. Interestingly, another study demonstrating transfer of 3D-MOT training in older adults also had their participants train by tracking three targets instead of four, but unfortunately did not compare younger and older adults (28).

A recent study compared learning of 3D-MOT in concussed older and younger adults and found that older age was negatively correlated with learning (29). They found flat learning curves in their older adult group, with younger adults exhibiting more than 2.5x the improvement on average as compared to the older adults. A principal difference between this study and those previously discussed was the choice to train participants on a tracking task with four targets instead of three. Unfortunately, it did not include any additional outcome measures to explore possible differences in transfer.

While previous studies and the results of the present thesis suggest that older adults are capable of tracking four targets, they are clearly at a massive disadvantage doing so compared to younger adults. Some older individuals are reportedly completely incapable of doing so except at speeds so slow that the stimuli are practically static (27). Several studies within the cognitive training literature demonstrate that adaptive training is more effective than non-adaptive or poorly-adapted training programs (30–32). Related to this concept is psychologist Lev Vygotsky's theory about the Zone of Proximal Development which holds not only that learning is optimized when task difficulty is just outside of an individual's current level of capability, but also that learning can be severely compromised when task difficulty is well beyond it (33). The appearance of a plateau in older adult performance by the sixth training session would seem to suggest that the task had become too taxing for many of them beyond a certain speed. Thus, with the benefit of hindsight, there is a strong argument to be made that the choice of training older adults with four targets rather than three may not have been optimal, interfering with their ability to benefit as much from later training sessions and for it to subsequently exhibit transfer.

The decision to use four targets was originally motivated by concerns that training with the easier task might reproduce previously discussed plateauing and subsequently limit possible transfer in younger adults. Additionally, there was a concern that using different training parameters with younger and older adults could have complicated comparisons down the line. Instead, the decision may have limited the ability to observe beneficial transfer in older adults due to the training not being well-adapted for them.

5.3.4 Future directions

While the results presented here do represent an incremental step forward, they also generate new questions and recommendations for future driving-related studies. Based on findings indicating potentially compromised learning, future studies comparing younger and older adult learning and transfer outcomes may want to opt to use different training parameters for each population to better optimize the adaptive paradigm. Additionally, future work should seek to clarify whether transfer to older adult driving performance outcomes could have been stronger with a potentially more optimized or longer training—perhaps one that initially requires tracking 3-targets before moving on to the harder 4-target condition.

While studies to come would undoubtedly benefit from recruiting more subjects, sample size is not the only potential limitation: enduring questions about whether simulator tasks are a generalizable approximation of real-world driving behaviour continue to be a specter looming over the field. Studies intending to extend this work should strongly consider taking inspiration from the methodologies used in the comparatively well-developed UFOV literature to supplement what was found here.

To that end, large-scale longitudinal studies comparing real-world driving outcomes such as self- and police-reported crashes, driving cessation and self-regulation, as well as traffic violations between individuals benefiting from cognitive training versus active controls represents one of the most technically feasible ways of acquiring a large amount of high-quality training outcome data. Like with the previously-discussed ACTIVE study, such a dataset would permit robust statistical methods; could address questions regarding the perceptual and cognitive mechanisms underlying differential 3D-MOT ability and how these related to driving ability; and have the potential to offer truly compelling evidence for a real-world benefit of this training when it comes to driving safety.

Such data would alleviate concerns about ecological validity and could neatly summarize literal years' worth of driving behaviour. A possible rejoinder exists, however, in the fact that real-world driving situations risking sudden collisions are relatively rare: a point in favour of simulator-based measures that can subject an individual to many such situations in short order and in total safety. Such natural experiments are also unable to explore the meaning and potential causes of observations like older adult driving speed self-regulation, the differential effects of adding secondary task requirements, or other more nuanced differences in driving behaviour that can only be captured by properly instrumented vehicles.

Naturally, conducting research of this scope poses immense challenges: it is unsurprising that ambitious studies like ACTIVE are rarities outside of the world of privately-funded clinical trials conducted by massive pharmaceutical and biotechnology companies. A sufficient accumulation of comparatively weaker evidence is likely required before marshalling the considerable resources required to conduct such a study would be justified. That said, this type of high-quality evidence may be the only way to truly establish the effectiveness of cognitive training beyond all reasonable doubts.

Another way to address concerns about the generalizability of driving simulator outcomes is through on-road or closed-circuit driving tasks. While this could quickly become unfeasible from a technical and financial standpoint, such studies would ideally use instrumented vehicles for objective driving metrics alongside subjective driving evaluations and capture long samples of driving behaviour. More realistically—and more in-line with existing studies—such research would most likely only be able to reflect a relatively small sample of driving behaviour. Still, given the impracticality of ever conducting "perfect" driving studies briefly touched upon here, converging evidence from well-designed studies employing a variety of different methodologies might be the next best thing.

Moving beyond academia and issues of demonstrating transfer of cognitive training, practical questions still remain about how to best make use of the information provided by cognitive assessments meant to distinguish safe from unsafe drivers. Future translational research needs to address the issue of developing appropriate cut-off scores highlighted by Bédard et al. and must also demonstrate that these scores have sufficient predictive power in the real-world.

Undoubtedly, this will involve assessing a battery of functional abilities such as visual functions that have been related to driving safety to supplement the limited information provided by cognitive measures. Longitudinal real-world outcomes will once again likely represent the best possible outcome data for this type of study considering how elegantly they address issues of generalizability and appropriate sampling duration for a behaviour as multifaceted as driving.

A related issue is eventually having to bring this knowledge and these measures to clinical settings. The potential value added by cognitive assessments are meaningless if clinicians are unaware of the best practices, resources, and reporting requirements when assessing older adult drivers intending to renew their licenses. Indeed, research shows that physicians are largely groping in the dark when it comes to this important responsibility that they often find themselves tasked with (34).

This also raises several practical issues about what to do with this information if it suggests an individual is not fit to drive. Would failing such a test battery result in immediate suspension of or conditions placed on someone's license? If not, then what should be the next steps? If so, to what extent should said individual be able to seek potential remediation… and how? Even if an individual is found to be unsafe to drive, would they still be fit to supervise a mostly autonomous self-driving vehicle if such a thing becomes commercially-available in the coming decades?

Simply developing and validating a hypothetical tool capable of reliably categorizing drivers as safe or unsafe does not address the serious psychosocial questions about forced driving cessation—and its consequences—that our society must grapple with sooner rather than later. While science can inform regulators and medical professionals, it cannot replace the important work and difficult discussions that lay ahead.

5.4 Conclusion

Choosing when to cease driving—or when to force the decision on others—is enormously challenging. Anything that could render this process easier would undoubtedly save many families a great deal of heartache and make physicians' lives easier. The results of the present thesis offer additional evidence that specialized tests of cognitive function can supplement currently used measures such as visual sensory tests when it comes to evaluating older adults intending to have their license renewed. The information provided by tests like NeuroTracker can eventually help doctors, individuals, and families make better-informed decisions regarding driving cessation and self-regulation.

Related to the goal of assessing cognitive abilities is that of enhancing them. While whether the improvements observed following cognitive training can ever transfer to performance on ecological tasks is still an open question, the promise of this possibility is clearly tantalizing enough for people worldwide to collectively spend billions of dollars yearly in the hopes of bettering themselves this way. Here it has been shown that 3D-MOT training can transfer to an untrained measure of visual information processing speed that has been repeatedly associated with driving performance and long-term driving outcomes—the UFOV. This suggests that the improvements observed following 3D-MOT training are not simply practice effects: it may indeed be improving some underlying cognitive ability (or abilities) required to perform the task at a high level.

In addition to this mid-level transfer, the third article included in this thesis presents evidence that the enhanced speed-of-processing demonstrated in the second article can translate to a measurable change in behaviour in a more complex task such as driving. While speeded reactions represent only a very small part of effective driving in the real-world, the results of studies such as this one offers a glimmer of hope that cognitive training interventions may one day be able to maintain drivers' safety well into their old age by delaying normal cognitive decline. The fact that benefits were demonstrated in healthy young adults supports continued evaluation of potential applications of adaptive cognitive training regimens to optimize performance even on everyday tasks.

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Annexes

1. Formulaire d'information et de consentement

Renseignements aux participants

Titre de l'étude : Effets d'un entrainement des habiletés perceptivo-cognitives sur les capacités de conduite automobile

Lieu de l'étude : Laboratoire de psychophysique et de perception visuelle
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Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et les inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel impliqué dans ce projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui ne vous paraitrait pas clair.

1. Introduction

Nous vous invitons à participer à ce projet de recherche portant sur l'effet d'un entrainement perceptivo-cognitif sur la conduite automobile dans un environnement virtuel. Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de lire attentivement et de comprendre les renseignements suivants. Si vous avez des questions concernant les modalités de l'étude ou bien sur le déroulement des séances, n'hésitez pas à nous joindre et nous nous ferons un plaisir d'y répondre.

Si une nouvelle information est susceptible de vous faire reconsidérer votre participation à l'étude, vous en serez avisé immédiatement.

2. Description de l'étude

• **But du projet** :

Présentement, la tendance est à l'élaboration de tests plus efficaces permettant de juger si un automobiliste est apte à la conduite automobile ou si, au contraire, il représente un danger potentiel pour les autres usagers de la route. Néanmoins, lorsque ces tests se révèlent être négatifs, et qu'une personne est déclarée inapte à la conduite, cela entraine de nombreuses répercussions négatives sur son autonomie et son bien-être. Dans le cadre de nos recherches, nous souhaitons que ces tests puissent être accompagnés de propositions permettant d'améliorer les capacités de conduite afin que cette cessation ne soit pas définitive ou soit retardée au maximum. Dans cet objectif, cette étude vise à évaluer l'influence d'un entrainement des habiletés perceptivo-cognitives sur les capacités de conduite automobile. Dans le cas ou cet apprentissage se révélerait être efficace, il pourrait être envisagé à plus grande échelle et permettre de prévenir les dégradations des performances de conduite. Les conséquences directes d'une telle avancée se feraient ressentir au niveau de la sécurité routière et permettraient à certains automobilistes de conserver leur autonomie plus longtemps.

Comme pour toute étude visant à évaluer l'impact d'un apprentissage, cette étude comporte 4 phases expérimentales.

- **Phase 1 : pré-entrainement**. Cette phase se déroule sur 2 séances (1h30 et 1h, respectivement) et vise à établir un seuil individuel.
- **Phase 2 : entrainement**. Cette phase se déroule sur 10 séances (45 minutes à 1h par séance) et vise à entrainer le participant sur une tâche visuelle.
- **Phase 3 : post-entrainement**. Cette phase se déroule sur 2 séances (1h30 et 1h, respectivement) et vise à comparer les performances obtenues après l'apprentissage à celles recueillies avant celui-ci (*i.e.* enregistrées lors du pré-entrainement) afin de pouvoir quantifier l'efficacité de cet apprentissage.

- **Phase 4 : rétention**. Cette phase se déroule sur une séance (1h30) et vise à étudier l'aspect robuste de l'apprentissage en répondant à la question suivante : l'apprentissage est-il assez consolidé pour persister dans le temps ?

Lors de ces différentes phases expérimentales, nous aurons à effectuer plusieurs mesures non-invasives. Lors de la **phase 1** de l'expérimentation, l'étudiant en charge du projet vous posera quelques questions sur vos habitudes de conduite, puis il évaluera votre acuité visuelle et stéréoscopique. Vous devrez ensuite répondre au questionnaire MoCA (Montreal Cognitive Assessment). Il s'agit d'un test de dépistage (et non de diagnostic) qui permettra de nous assurer que vous êtes apte à comprendre et signer le formulaire de consentement et que vous n'avez aucun trouble cognitif qui pourrait fausser les résultats de l'étude. En cas d'anomalie, vous serez référé à la clinique Universitaire de Psychologie de l'Université de Montréal (Pavillon Marie-Victorin 1525 boulevard Mont-Royal ouest).

Lors des phases **1, 3 et 4**, vous serez amené à effectuer plusieurs tests.

- **Tests visuels :** le NeuroMinder, le NeuroTracker et le test de UFOV. Les deux premiers tests nous permettront d'avoir des données intéressantes concernant votre capacité à discerner les contrastes de luminance et de texture, mais aussi votre capacité à suivre des objets en mouvements. Le dernier test nous permettra d'évaluer votre capacité à déployer votre attention visuelle sur différentes zones du champ visuel.
- **Electroencéphalographie (EEG) :** l'EEG est une mesure non-invasive qui nous permet de mesurer les courants électriques issus de votre cerveau par l'intermédiaire d'un bonnet élastique (similaire à un bonnet de bain) posé sur votre tête. En effet, lorsque les neurones communiquent entre eux, une décharge électrique est générée et se diffuse à travers les différents tissus corticaux. Ainsi, le bonnet placé sur votre tête nous permet d'enregistrer ces courants électriques et d'en apprendre plus sur les bases neuronales de l'apprentissage. Au cours de ces enregistrements, il vous sera simplement demandé de rester calmement assis dans un fauteuil, les yeux ouverts ou les yeux fermés pour une durée totale de 10 minutes.
- **Simulateur de conduite :** Après quelques explications concernant le simulateur automobile, vous pourrez prendre place dans l'habitacle et vous démarrerez un scénario test de conduite d'une durée de 12 minutes afin de vous familiariser avec l'environnement virtuel que confère le simulateur. Suite à cette phase de familiarisation, nous débuterons l'expérimentation. Celle-ci se compose de deux scénarios de conduite différents, d'une durée de 6 minutes chacun. Lors de ces scénarios, il vous sera demandé de conduire comme vous en avez l'habitude. De plus, chaque parcours sera séparé par une pause de 5 minutes où vous pourrez vous détendre et poser d'éventuelles questions à l'étudiant chercheur. Lorsque vous serez installé dans le simulateur automobile, vous serez équipé de lunettes qui nous permettront d'enregistrer le mouvement de vos yeux en temps réel. Ces mesures nous

permettront de savoir comment les informations visuelles pertinentes pour la conduite automobile sont repérées.

Enfin, lors de la **phase 2**, vous serez amené à effectuer 10 séances d'environ 45 minutes à 1h durant lesquelles vous aurez à effectuer une tâche visuelle. Ces 10 séances se dérouleront à une fréquence de deux fois par semaine et seront fixées selon vos disponibilités. Selon le groupe dans lequel vous serez réparti (répartition aléatoire n'ayant aucun rapport avec vos performances), vous aurez, soit à effectuer une tâche de discrimination visuelle soit à effectuer une tâche de suivi d'objets multiples. Dans les deux cas, ces séances d'apprentissage se dérouleront devant un écran 3D associé à des lunettes 3D que vous porterez. Vous serez confortablement assis pendant l'exécution de ces sessions.

Ci-dessous, un schéma récapitulatif du déroulement de l'expérimentation :

Phase 1 [2h + 2h]	**Phase 2** [10 x 30m]	**Phase 3** [2h + 1h]	**Phase 4** [2h00]
- Acuité visuelle, stéréo-scopique et MoCA - Tests visuels - EEG - Simulateur de conduite - Enregistrement mouvement des yeux	Discrimination visuelle **Ou** Suivi d'objets multiples	- Tests visuels - EEG - Simulateur de conduite - Enregistrement mouvement des yeux	- EEG - Simulateur de conduite - Enregistrement mouvement des yeux

3. Conditions de participation

Notre projet admet toute personne volontaire ayant donné son consentement signé au préalable. Chaque participant devra appartenir à certains critères énoncés ci-dessous; et devra avoir effectué un examen visuel complet dans l'année précédente. Si vous n'avez pas subi d'examen visuel au cours de la dernière année, l'étudiant en charge du projet vous fera un examen visuel partiel (sans dilatation pupillaire) sous la supervision d'un optométriste membre de l'association des optométristes du Québec. L'étudiant chercheur est formé pour effectuer un examen visuel complet, et une salle d'examen ainsi que tout le matériel optométrique nécessaire est disponible dans l'enceinte du laboratoire de psychophysique et de perception visuelle. Si une anomalie devait être découverte, vous seriez référé à la Clinique Universitaire de la Vision pour un examen approfondi. Toutefois, l'examen visuel réalisé dans le cadre de l'étude ne remplace en rien un examen complet effectué chez votre optométriste habituel.

Pour participer à l'étude, il est essentiel que vous répondiez aux critères suivants :

- Avoir entre 25 et 35 ans inclus, ou avoir entre 65 et 75 ans inclus ;
- Etre détenteur du permis de conduire ;
- Avoir une bonne vision de loin corrigée en lunettes ou en verres de contact ;
- Avoir une bonne vision en trois dimension (3D) ;
- Avoir une bonne santé générale et oculaire.

En revanche, vous ne pourrez pas participer à notre étude si :

- Vous avez déjà participé à une étude sur la conduite automobile ;
- Vous êtes sous médication ayant une influence sur l'état de vigilance ou sur l'attention ;
- Vous souffrez de l'une des maladies suivantes :
    - Troubles de l'équilibre
    - Problèmes cardiaques
    - Troubles vestibulaires, épilepsie
    - Diabète
    - Maladie de Parkinson
    - Maladie d'Alzheimer ou toute autre démence
    - Toute anomalie ou pathologie oculaire telles que (amblyopie, glaucome, strabisme, dystrophie cornéenne, infection oculaire active)

4. Participation volontaire

Votre participation à ce projet de recherche est tout à fait volontaire. Vous avez le choix d'y participer ou non, sans aucune retombée sur votre décision. Vous pouvez également vous retirez de ce projet à n'importe quel moment, et cela sans justification. Vous devrez simplement avertir dès que possible le chercheur responsable du projet ou l'un des membres de l'équipe.

Le chercheur responsable du projet de recherche ou l'organisme subventionnaire peuvent aussi mettre fin à votre participation si vous ne respectez pas les consignes du projet de recherche ou si cela n'est plus dans votre intérêt. Par ailleurs, l'organisme subventionnaire ou le Comité d’éthique de la recherche en santé (CÉRES) de l’Université de Montréal peuvent également mettre fin au projet, notamment pour des raisons de sécurité ou de faisabilité.

En cas de retrait ou d’exclusion, les renseignements qui auront été recueillis au moment de votre retrait seront détruits.

Votre rémunération dépendra du temps d’expérimentation passé au Laboratoire. Si vous souhaitez arrêter l’étude en cours de route, le montant auquel vous aurez droit sera donc fonction du temps que vous aurez consacré pour notre recherche.

5. Avantages et bénéfices

Le participant ne recevra aucun bénéfice individuel direct pour sa collaboration à ce projet, mais il aidera à accroitre nos connaissances dans le domaine de la conduite automobile.

6. Risques et inconvénients

Vivre une expérience en réalité virtuelle peut avoir quelques effets indésirables minimes. En effet, lors des simulations de conduite vous pourrez ressentir quelques inconforts légers tels que le mal de tête, une légère perte d'équilibre, des nausées ou une vision embrouillée potentiellement liée à une fatigue visuelle. Ces symptômes n'ont aucun effet à long terme et cessent dès la sortie de l'environnement virtuel. Ces inconforts sont toutefois rarement rapportés, et s'ils le sont, ils sont alors minimes. Durant l'expérimentation, l'étudiant en charge du projet sera présent dans la pièce du simulateur afin de vous assurer un maximum de sécurité. Dans le cas où vous ressentiriez un malaise, l'expérience sera automatiquement arrêtée.

Enfin, les déplacements au laboratoire et le temps consacré à notre étude constituent les principaux inconvénients associés à cette recherche. C'est pourquoi une compensation de 15 $ par séance vous sera offerte.

7. Conservation des données et confidentialité

Durant votre participation à ce projet, le chercheur et son équipe recueilleront dans un dossier de recherche les renseignements vous concernant nécessaires pour répondre aux objectifs scientifiques.

Tous les renseignements recueillis demeureront strictement confidentiels. Vous ne serez identifié que par un numéro de code auquel seule l’équipe de recherche aura accès. La clé du code, reliant votre nom à votre dossier de recherche, sera conservée par le chercheur responsable.

Les données de recherche seront conservées sous clé pendant sept ans après la fin de l'étude et seront détruites par la suite. Advenant du cas où vous vous retirez du projet, vous pourrez demander à ce que les données vous concernant soient détruites.

Vous avez le droit de consulter votre dossier de recherche pour vérifier les renseignements recueillis, et les faire rectifier au besoin, et ce, aussi longtemps que le chercheur responsable du projet ou l'établissement détiennent ces informations. Cependant, afin de préserver l'intégrité scientifique du projet, vous pourriez n'avoir accès à certaines de ces informations qu'une fois votre participation terminée.

Pour des raisons de surveillance et de contrôle de la recherche, votre dossier pourra être consulté par une personne mandatée par l'organisme subventionnaire et le Comité d'éthique de la recherche des sciences de la santé (CÉRES) de l'Université de Montréal. Toutes ces personnes respecteront la politique de confidentialité.

De plus, il est possible que vos données de recherche soient publiées dans des journaux scientifiques. En revanche, aucune information ne permettant de vous identifier ne sera divulguée dans un article scientifique.

8. Compensation et indemnisation

Une compensation monétaire de 15$/séance est offerte aux participants, que la séance soit entièrement complétée ou non (soit 225$ pour l'ensemble de l'étude). Les fonds disponible aux fins de compensation des participants à l'étude proviennent de la Chaire industrielle CRSNG-ESSILOR dont Jocelyn Faubert est le titulaire. La référence de l'octroi des fonds dans dossier de la Chaire industrielle CRSNG est : IRCPJ305729-08.

9. Responsabilité de l'équipe de recherche

En signant le présent formulaire d'information et de consentement, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs et l'établissement de leurs responsabilités civile et professionnelle. Si vous deviez subir un préjudice ou une lésion quelle qu'elle soit pendant votre participation à ce projet, vous recevrez tous les soins et services requis par votre état de santé, sans frais de votre part.

10. Communication des résultats

Les résultats de l'étude seront accessibles aux participants sur le site du laboratoire de psychophysique et perception visuelle : http://vision.opto.umontreal.ca/. L'affichage se fera dans l'année suivant la fin de l'expérimentation.

11. Personnes – ressources

Si vous avez des questions au sujet de cette étude, vous pouvez communiquer à tout moment avec les personnes suivantes :

Jesse Michaels (étudiant chercheur)

Romain Chaumillon (co-directeur de recherche) : ☎ (514) 343-6111 # 36873

Delphine Tranvouez-Bernardin (co-directeur de recherche) :☎ (514) 343-6111 # 20433

Jocelyn Faubert (Directeur de recherche) : ☎ (514) 343-7289

Si un problème survient pendant l'étude, l'étudiant chercheur sera toujours près de vous pour vous aider et répondre à vos questions. Vous pouvez aussi trouver tous les renseignements nécessaires sur le site Internet du Laboratoire de psychophysique et perception visuelle de l'école d'optométrie de l'Université de Montréal : http://vision.opto.umontreal.ca/

Pour toute question d'ordre éthique concernant les conditions dans lesquelles se déroule votre participation à ce projet, vous pouvez en discuter avec le responsable du projet, expliquer vos préoccupations au conseiller en éthique du Comité d'Ethique de la Recherche En Santé (CERES) :

- Par courriel : ceres@umontreal.ca
- Par téléphone : (514) 343-6111 poste 2604
- Site web : htttp://recherche.umontreal.ca/participants.

Toute plainte concernant cette recherche peut être adressée à l'ombudsman de l'Université de Montréal, au numéro de téléphone (514) 343-2100 ou à l'adresse courriel ombudsman@umontreal.ca. L'ombudsman accepte les appels à frais virés. Il s'exprime en français et en anglais et prend les appels entre 9h et 17h.

12. Surveillance des aspects éthiques du projet de recherche

Le Comité d'éthique de la recherche des sciences de la santé a approuvé ce projet de recherche et en assure le suivi. De plus, il approuvera toute modification apportée au formulaire d'information et de consentement et au protocole de recherche.

13. Signatures

<u>Titre de l'étude :</u> « Effet d'un entrainement perceptivo-cognitif sur les capacités de conduite automobile»

Chercheur Principal : Jocelyn Faubert, Ph.D
Chercheur associé : Delphine Tranvouez-Bernardin, Ph.D
Stagiaire postdoctoral associé : Romain Chaumillon, Ph.D
Étudiant chercheur : Jesse Michaels

<u>Signature du candidat :</u>

J'ai pris connaissance du formulaire d'information et de consentement. Je reconnais qu'on m'a expliqué le projet, qu'on a répondu à mes questions à ma satisfaction et qu'on m'a laissé le temps voulu pour prendre une décision. Je consens à participer à ce projet de recherche aux conditions qui y sont énoncées. Une copie signée et datée du présent formulaire d'information et de consentement me sera remise.

Je consens à ce que mon dossier optométrique soit consulté par l'équipe de recherche pendant 8 mois afin d'obtenir les résultats des tests optométriques nécessaires à la réalisation de l'étude :

OUI NON

____ Date : ________________
Nom et signature du participant

<u>Engagement et signature du chercheur :</u>

Je certifie que l'on a expliqué au participant les termes du présent formulaire d'information et de consentement, que l'on a répondu aux questions que le participant avait à cet égard et que l'on lui a clairement indiqué qu'il demeure libre de mettre un terme à sa participation, et ce, sans aucune conséquence négative.

Je m'engage avec l'équipe de recherche à respecter ce qui a été convenu au formulaire d'information et de consentement et à en remettre une copie signée au participant.

____ Date : ________________
Nom et signature du chercheur responsable du projet de recherche

<u>Signature de la personne qui a obtenu le consentement si différente du chercheur responsable du projet de recherche :</u>

J'ai expliqué au participant les termes du présent formulaire d'information et de consentement et j'ai répondu aux questions qu'il m'a posées.

____ Date : ________________
Nom et signature de la personne qui obtient le consentement

2. Simulator Sickness Questionnaire

De façon générale, vous arrive-t-il de ressentir les symptômes suivants; si oui, à quelle intensité ?

Generally, do you experiment these symptoms and how intense is it?

Questionnaire d'inconfort subjectif (Simulator Sickness Questionnaire)	Non (no)	Léger (light)	Modéré (moderate)	Sévère (severe)
1. Malaise général (General discomfort)				
2. Fatigue (Fatigue)				
3. Mal de Tête (Headache)				
4. Yeux fatigués (Eyestrain)				
5. Difficultés de mise au point (Difficulty focusing)				
6. Augmentation de salivation (Salivation increase)				
7. Sueurs (Sweating)				
8. Nausées (Nausea)				
9. Difficultés de concentration (Difficulty concentrating)				
10. « Tête pleine » ("Fullness of the head")				
11. Vision embrouillée (Blurred vision)				
12. Etourdissements yeux ouverts (Dizziness eyes open)				
13. Etourdissements yeux fermés (Dizziness eyes close)				
14. Vertiges (Vertigo)				
15. Mal au Cœur (Stomach awareness)				
16. Éructation (Rot) (Burping)				
17. Autres (Other)				

Au cours de l'exposition en réalité virtuelle ou juste après, avez-vous ressenti les symptômes suivants et, si oui, à quelle intensité ?

During virtual reality exposure or just after, did you experience these symptoms and how intense were they?

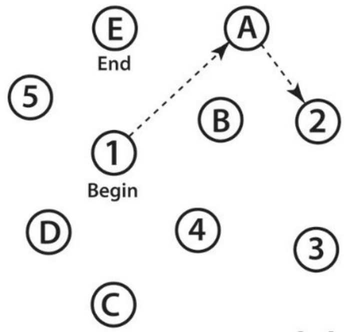
Questionnaire d'inconfort subjectif (Simulator Sickness Questionnaire)	Non (no)	Léger (light)	Modéré (moderate)	Sévère (severe)
1. Malaise général (General discomfort)				
2. Fatigue (Fatigue)				
3. Mal de Tête (Headache)				
4. Yeux fatigués (Eyestrain)				
5. Difficultés de mise au point (Difficulty focusing)				
6. Augmentation de salivation (Salivation increase)				
7. Sueurs (Sweating)				
8. Nausées (Nausea)				
9. Difficultés de concentration (Difficulty concentrating)				
10. « Tête pleine » ("Fullness of the head")				
11. Vision embrouillée (Blurred vision)				
12. Etourdissements yeux ouverts (Dizziness eyes open)				
13. Etourdissements yeux fermés (Dizziness eyes close)				
14. Vertiges (Vertigo)				
15. Mal au Cœur (Stomach awareness)				
16. Éructation (Rot) (Burping)				
17. Autres (Other)				

3. Montreal Cognitive Assessment (MoCA)

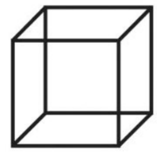
MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education : Date of birth :
Sex : DATE :

VISUOSPATIAL / EXECUTIVE



[ ]



Copy cube

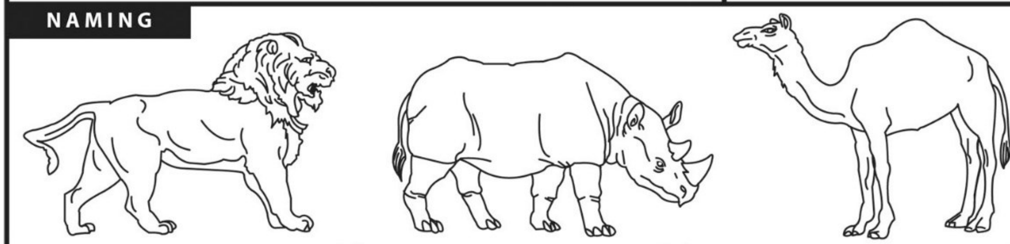
[ ]

Draw CLOCK (Ten past eleven)
(3 points)

[ ] Contour [ ] Numbers [ ] Hands

POINTS ___/5

NAMING



[ ] [ ] [ ]

___/3

MEMORY		FACE	VELVET	CHURCH	DAISY	RED	
Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.	1st trial						No points
	2nd trial						

ATTENTION

Read list of digits (1 digit/ sec.). Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2 ___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B ___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt** ___/3

LANGUAGE

Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ] ___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words) ___/1

ABSTRACTION

Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler ___/2

DELAYED RECALL	Has to recall words WITH NO CUE	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]	Points for UNCUED recall only	___/5
Optional	Category cue							
	Multiple choice cue							

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City ___/6

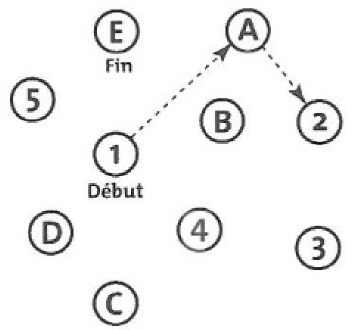
 www.mocatest.org Normal ≥26 / 30 TOTAL ___/30

Administered by: ______________________ Add 1 point if ≤ 12 yr edu

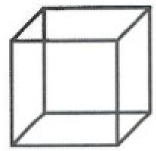
MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 **FRANÇAIS**

NOM :
Scolarité : **Date de naissance :**
Sexe : **DATE :**

VISUOSPATIAL / ÉXÉCUTIF



[ ]



Copier le cube

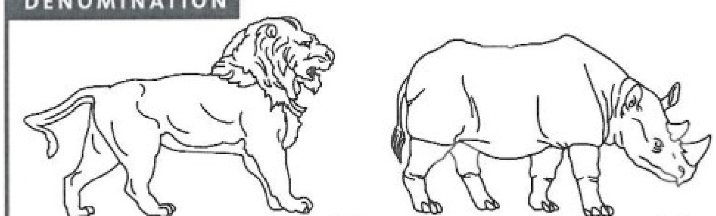
[ ]

Dessiner HORLOGE (11 h 10 min)
(3 points)

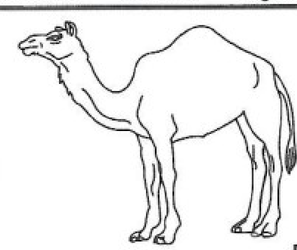
[ ] Contour [ ] Chiffres [ ] Aiguilles

POINTS: __/5

DÉNOMINATION



[ ] [ ]



[ ]

__/3

MÉMOIRE

Lire la liste de mots, le patient doit répéter. Faire 2 essais même si le 1er essai est réussi. Faire un rappel 5 min après.

	VISAGE	VELOURS	ÉGLISE	MARGUERITE	ROUGE
1er essai					
2ème essai					

Pas de point

ATTENTION

Lire la série de chiffres (1 chiffre/ sec.).

Le patient doit la répéter. [ ] 2 1 8 5 4
Le patient doit la répéter à l'envers. [ ] 7 4 2 __/2

Lire la série de lettres. Le patient doit taper de la main à chaque lettre A. Pas de point si ≥ 2 erreurs

[ ] FBACMNAAJKLBAFAKDEAAAJAMOFAAB __/1

Soustraire série de 7 à partir de 100. [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65

4 ou 5 soustractions correctes : **3 pts**, 2 ou 3 correctes : **2 pts**, 1 correcte : **1 pt**, 0 correcte : **0 pt** __/3

LANGAGE

Répéter : Le colibri a déposé ses œufs sur le sable . [ ] L'argument de l'avocat les a convaincus. [ ] __/2

Fluidité de langage. Nommer un maximum de mots commençant par la lettre «F» en 1 min [ ] ____ (N≥11 mots) __/1

ABSTRACTION

Similitude entre ex : banane - orange = fruit [ ] train – bicyclette [ ] montre - règle __/2

RAPPEL

		VISAGE	VELOURS	ÉGLISE	MARGUERITE	ROUGE	Points pour rappel SANS INDICES seulement
	Doit se souvenir des mots SANS INDICES	[ ]	[ ]	[ ]	[ ]	[ ]	
Optionnel	Indice de catégorie						
	Indice choix multiples						

__/5

ORIENTATION

[ ] Date [ ] Mois [ ] Année [ ] Jour [ ] Endroit [ ] Ville __/6

 www.mocatest.org Normal ≥ 26 / 30 **TOTAL** __/30

Ajouter 1 point si scolarité ≤ 12 ans

Administré par : ____________________

4. Ethics approval certificate

Université de Montréal

Comité d'éthique de la recherche en santé

13 octobre 2016

Objet: Approbation éthique – « Effets d'un entraînement des habiletés perceptivo-cognitives sur les capacités de conduite automobile »

M. Jesse Michaels,

Le Comité d'éthique de la recherche en santé (CERES) a étudié le projet de recherche susmentionné et a délivré le certificat d'éthique demandé suite à la satisfaction des exigences précédemment émises. Vous trouverez ci-joint une copie numérisée de votre certificat; copie également envoyée à votre directeur/directrice de recherche et à la technicienne en gestion de dossiers étudiants (TGDE) de votre département.

Notez qu'il y apparaît une mention relative à un suivi annuel et que le certificat comporte une date de fin de validité. En effet, afin de répondre aux exigences éthiques en vigueur au Canada et à l'Université de Montréal, nous devons exercer un suivi annuel auprès des chercheurs et étudiants-chercheurs.

De manière à rendre ce processus le plus simple possible et afin d'en tirer pour tous le plus grand profit, nous avons élaboré un court questionnaire qui vous permettra à la fois de satisfaire aux exigences du suivi et de nous faire part de vos commentaires et de vos besoins en matière d'éthique en cours de recherche. Ce questionnaire de suivi devra être rempli annuellement jusqu'à la fin du projet et pourra nous être retourné par courriel. La validité de l'approbation éthique est conditionnelle à ce suivi. Sur réception du dernier rapport de suivi en fin de projet, votre dossier sera clos.

Il est entendu que cela ne modifie en rien l'obligation pour le chercheur, tel qu'indiqué sur le certificat d'éthique, de signaler au CERES tout incident grave dès qu'il survient ou de lui faire part de tout changement anticipé au protocole de recherche.

Nous vous prions d'agréer, Monsieur, l'expression de nos sentiments les meilleurs,

Dominique Langelier, présidente
Comité d'éthique de la recherche en santé (CERES)
Université de Montréal

DL/GP/gp
c.c. Gestion des certificats, BRDV
Jocelyn Faubert, professeur titulaire, École d'optométrie
Delphine Bernardin, professeure associée, École d'optométrie
p.j. Certificat #16-130-CERES-D

adresse postale
C.P. 6128, succ. Centre-ville
Montréal QC H3C 3J7

3744 Jean-Brillant
4e étage, bur. 430-11
Montréal QC H3T 1P1

Téléphone : 514-343-6111 poste 2604
ceres@umontreal.ca
www.ceres.umontreal.ca

5. Study advertisements posted in public areas

Université de Montréal   FAUBERT LAB

PARTICIPANT(E)S RECHERCHÉ(E)S POUR UNE ÉTUDE SUR LA CONDUITE AUTOMOBILE

Caractéristiques recherchées :

- Hommes ou Femmes
- Avoir **65 ans et plus**
- Avoir une **bonne vision** (ou une vision corrigée avec des lunettes)
- Avoir une **bonne santé générale et oculaire**
- **Avoir un permis de conduire valide**
- Avoir eu un examen de la vue dans la dernière année

Durée de l'étude: 15 séances sur 7 semaines (horaire flexible)

Compensation financière : 15$/séance ($225 totale)

Lieu : Laboratoire de psychophysique et de perception visuelle
3744, rue Jean Brillant
Montréal, QC H3T 1P1 Canada

Pour toutes questions, vous pouvez vous adresser à :