Looking to the Future of Visual Assessment using Driving Simulation

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Abstract
Visual function is considered uniquely important for driving because it provides multiple critical sources of information that when combined ensures successful steering. There are, however, additional cognitive functions that are essential for the driver to be able to dynamically respond to the world and make predictions about the scene, as well as the behaviour of other road users. Given the complexity of driving through a busy urban environment it should be no surprise that simple tests of visual acuity seem to have weak explanatory power in terms of increased crash risk when driving. Despite this, fitness to drive still includes a formal assessment of visual acuity, with poor scores being used to revoke the driving licence. The "gold standard" measure of driving ability remains the on-road driving test but compared to visual tests they are fairly uncontrolled, susceptible to great variation depending on the road conditions, and are unable to reliably detect subtle visual deficits. To address some of the limitations of these existing tests we use examples from two simulator settings (steering control and hazard detection) that highlight the merits of using driving simulation in order to control the visual conditions and probe specific functional capabilities of drivers. When used in conjunction with visual tests these methods will not only determine whether the core functions of driving are intact but also be able to provide richer feedback to individuals about the nature of their deficits. There are many exciting possibilities using simulation techniques to establish predictive relationships between routine visual testing and driving performance, ultimately aiming for better, more reliable assessment of fitness to drive.

Sammendrag
Synsfunksjonen betraktes som enestående viktig for bilkjøring fordi den bidrar til flere kritiske informasjonskilder som sammen sikrer trygg kontroll av bilen. Men det finnes i tillegg andre kognitive funksjoner som er nødvendige for at en bilfører skal kunne reagere dynamisk og kunne forutse både hendelser i trafikkbildet og andre trafikanters handlinger. Tatt i betraktning kompleksiteten av å kjøre i trafikkerte, tettbygde strøk, er det ikke overraskende at en enkel test av synsstyrke sjelden kan forklare fullstendig risikoen for kollisjoner ved bilkjøring. Til tross for dette brukes fortsatt synsstyrke som et mål i den formelle undersøkelsen når man skal avgjøre om en person er egnet til å føre motorvogn, og dårlige resultater på synstesten fører til inndragelse av førerkortet. Kjøreevne måles fortsatt med praktisk prøve, men sammenlignet med tester av synsfunksjonen er disse prøvene vanskelige å kontrollere, sterkt varierende avhengig av veiforholdene, og ikke i stand til å avsløre små synsdefekter. For å studere noen av begrensningene ved disse eksisterende prøvene bruker vi eksempler fra to simulatorsettinger (styrekontroll og evne til å oppdage fare) som viser fordelene med å bruke kjøresimulator for å kontrollere synsforholdene og teste bestemte funkjonelle ferdigheter hos bilførere. Brukt sammen med testing av synsfunksjonen vil disse metodene ikke bare kunne avgjøre om grunnleggende kjøreferdigheter tilfredsstillende, men også kunne gi mer omfattende tilbakemelding om type defekter hos en person. Det finnes mange spennende muligheter i bruk av simulatorteknikker for å etablere forutsigbare forbindelser mellom standard testing av syn og kjøreegenskaper, med bedre og mer pålitelig vurdering av egnethet til å føre motorvogn som det endelige mål.

Introduction
Humans possess the ability to carry out an extraordinary repertoire of skilled actions. The capability to learn these skills originally evolved from the need to perform a variety of perceptual-motor tasks that aided survival (e.g. finding food and a mate, whilst avoiding predation). These abilities now support a range of locomotor behaviours, fundamental for a variety of interactions humans have with the world. Indeed, the functions that support movement in the world have proved to be exceptionally adaptable and have enabled humans to engage with tools to a degree that sets them apart from any other animal species on earth. Amongst the tools that have been adopted, new modes of transport could be considered some of the most powerful. The human central-nervous system shows a remarkable ability to adapt the functions underpinning walking and running and translate them to the control of high-speed vehicles (such as cars). Humans can drive for many hours, even when visual information is degraded (e.g. night time or blizzard conditions), but the apparent ease with which the human perceptual-motor system copes with these conditions means that it is easy to underestimate the sheer scale of the demands. Even minor impairments in function could have major significance in terms of driver safety. This article considers the best way to gather robust measures of performance to inform both the individual (who is considering whether they are safe to continue driving) and driving licence authorities (who often make the final decision about which individuals are safe to drive).

Driving has become a routine, ubiquitous human activity in modern life. This is mainly due to the flexibility and utility of the road infrastructure, supporting international freight transportation as well as local travel for individuals dropping children at school and/or commuting to work each day. Of course, modern cities have all the necessary services and facilities contained in a small geographic region, so driving is only one of a number of transport options for daily life (including public transport, cycling or walking). In contrast, for those living in rural locations, driving is often considered essential because the travel distances are great (essential services are distributed far apart) and the transport infrastructure is sparse (public transport have limited timetables) limiting alternative modes of transport (Gray, Farrington, Shaw, Martin, & Roberts, 2001; Velaga, Beecroft, Nelson, Corsar, & Edwards, 2012).

Part of the utility of driving is that it is generally safe, with many thousands of miles travelled each year by each driver without incident. Unfortunately, it remains the case that driving is one of the major causes of serious injury worldwide (World Health Organization, 2015) with 1732 reported road deaths on UK roads alone in 2015 (Department for Transport, 2016). For this reason there are usually strict training and performance requirements for acquiring and retaining a driving licence. When learning to drive performance criteria must be met to gain a driving licence and then the general assumption is that most individuals will maintain and improve their driving skills over time as they gain experience of a wide range of driving conditions. The main exception to this pattern is when a medical condition is acquired that can affect driving capability, e.g. re-

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covering from a major brain injury such as stroke. A variety of specific assessments have been endorsed by driving licencing authorities to determine sufficient/intact function for those with an illness that may have impaired driving. However, for the majority of older drivers, rather than experiencing a sudden discrete disease event, there is a gradual decline in perceptual, motor and cognitive functions that falls under the categorisation of "healthy-ageing" (Anstey & Wood, 2011; Anstey, Wood, Lord, & Walker, 2005; Bédard, Campbell, Riendeau, Maxwell, & Weaver, 2016). The rate of decline varies hugely across individuals, dependent on genetic and lifestyle factors (Raz et al., 2005), but in many countries (e.g. Denmark, UK, Finland, Netherlands, New Zealand, Portugal and Norway) drivers reaching a threshold age are subjected to license renewal requirements to ensure that they are still capable of driving safely (Organisation for Economic Co-operation and Development, 2001; Siren & Haustein, 2015; Norwegian Public Roads Administration, 2014). Given the current demographics of many countries (i.e. an ageing population; United Nations, Department of Economic and Social Affairs, Population Division, 2015) it seems that these cases are set to soar over the coming decades (Anstey, Eramudugolla, Ross, Lautenschlager, & Wood, 2016), and there will be a growing societal challenge to ensure that our roads remain safe for the maximum number of road users.

The challenge stems from the fact that driving licencing authorities have two goals that push in opposite directions: i) to regulate driving to keep roads safe, and ii) to restrict as few drivers as possible to keep society and the economy mobile. The simplest way to make roads safe would be to restrict all road users, whilst at the opposite extreme, road users could be maximised by removing all restrictions. Clearly both solutions are absurd, but serve to highlight the challenge in finding the right balance between restricting road use for individuals deemed unsafe (with an overall benefit of improving road safety for society as a whole) whilst not barring large populations from the road (because of the major negative consequences for those individuals; (Edwards, Lunsman, Perkins, Rebok, & Roth, 2009)). The growing societal challenge is the increase in older adult numbers. Older adults tend to rely more upon cars for personal mobility because they are less able to walk or take public transport (Doebler, 2015), but these are the same individuals that are most likely to be impaired in their driving abilities. It is, therefore, essential to improve our understanding of the human perceptual, motor and cognitive function requirements for driving especially in relation to declines associated with injury, disease and old age.

To impose restrictions driving licencing authorities require some form of measurement of performance that relates to driving competence. There have been surprisingly few advances in the way that drivers are tested, with the on-road driving tests remaining the "gold standard" (i.e. legally recognised) measurement of capability (Fox, Bowden, & Smith, 1998; Ross, Ponsford, Di Stefano, Charlton, & Spitz, 2016). Despite the various limitations of on-road driving tests (as highlighted in the section below) they remain the reference against which other methods (e.g. off-road testing or driving simulation) are compared ((Akinwuntan et al., 2006; Bédard, Parkkari, Weaver, Riendeau, & Dahlquist, 2010; Classen et al., 2013; George & Crotty, 2010; Hird, Vetivelu, Saposnik, & Schweizer, 2014; Iverson et al., 2015). The future of driving assessment must establish which metrics best capture the necessary and sufficient perceptual, motor and cognitive functions for driving to ensure that those with the requisite capabilities are allowed to continue to drive. Irrespective of the measures used, or the groups being considered, there is a question at the heart of this issue: what level of functional impairment is acceptable for society given the (often uncertain) associated increase in risk?

Testing Visual Function for Driving

Within "healthy-ageing" groups it is likely that visual impairments will be one of the most common reasons from preclusion from driving (Owsley & McGwin, 2010). There are three key reasons why this would be the case:

1. *occurance*: there are universal age-related changes to eye structure and function that usually require some degree of corrections (e.g. presbyopia, Glasser & Campbell, 1998). "Healthy" older adults will regularly present to an optometrist/ophthalmologist because of decline in visual function. Current estimates are that over 30% of those over 50 years old having some cataract formation (Rochtchina et al., 2003) and cataract surgery (the most common operation in the UK NHS; Frampton, Harris, Cooper, Lotery, & Shepherd, 2014) is now a routine procedure, that is shown to markedly improve driving safety (Joanne M. Wood & Black, 2016).
2. *functional relevance*: visual function is considered crucial for the control of driving, with the human visual system rapidly sampling multiple information sources via the active gaze fixation system (Wilkie & Wann, 2003; Wilkie, Wann, & Allison, 2008; 2008). Of course, the term "visual function" actually encompasses a wide range of separate functions that detect distinct features (e.g. motion, colour, edges) that themselves undergo further neural processing to support higher level percepts such as object recognition or direction of motion. In some cases high-acuity signals from the point of fixation will be needed (e.g. reading a road sign), but in other cases global signals from across the whole field are required (Georgios K. Kountouriotis, Mole, Merat, & Wilkie, 2016, e.g. optic flow).
3. *measureable*: In the UK, the driving standards are in part enshrined by law, with prescribed vision standards (e.g. the "number-plate test" that can be carried out in the car, alongside visual acuity requirements)[1]. Because of the facilities available in modern optometric clinics it can be (in principle) relatively straightforward to gain reliable measures of core visual functions. Reliable measures are critical when considering the huge impact of revoking/precluding a driving licence on an individual, and the possibility of litigation if test results are incorrect. In the UK a minimum binocular visual acuity of 6/12 is required as well as the ability to read in good light (with corrective lenses if necessary) a vehicle registration plate from a distance of 20 metres (the "number-plate test"). The visual field standards (for Group 1 car drivers) require a width of horizontal field of at least 120° (with at least 50° on either side of fixation) and no significant defect either within or encroaching into the central 20° from fixation. Any driver unable to meet these standards must not drive and must notify the Driver and Vehicle Licensing Agency (DVLA), which will refuse or revoke a licence (Driver and Vehicle Licensing Agency, 2016).

One of the issues underlying the use of these visual tests is the presumption that there is a direct link between measurable visual function (such as visual acuity and visual fields) and driving performance. However, the evidence for such direct links is, at best, mixed (see Owsley & McGwin, 2010; Joanne M. Wood & Black, 2016, for reviews). Driving is a complex dynamic task where success hinges on how the perceptual-motor system

[1]The European Eyesight Working Group defined the "New Standards for the Visual Functions of Drivers" in 2005, which informed minimum standards for vision and driving specified by the European Commission in 2009. In 2012/13 the UK (after public consultation) amended those vision standards that had previously been below the minimum EC standards with changes to both visual acuity and visual field standards.

samples information from an ever-changing scene (Lappi, 2014) rather than on the perceptual limits assessed by static visual assessments. The continued use of such tests in legislation risks falsely excluding individuals who are able to drive despite poor visual function in some tests, and/or falsely accepting individuals who have adequate static visual function but may be impaired in other functions also relevant to driving (e.g. cognitive function).

It is worth comparing the properties of visual decline as outlined above with commensurate decline in cognitive function which also regularly accompanies old age and could have severe implications for road safety (Anstey, Eramudugolla, Chopra, Price, & Wood, 2017; Anstey & Wood, 2011). Cognitive decline can manifest in various ways (e.g. impaired memory, attention, multi-tasking; Gunning-Dixon and Raz, 2000; Kray and Lindenberger, 2000; Verhaeghen and Salthouse, 1997) but it is unclear how to measure the specific impact of such functions on driving. There is consistent evidence that tests of visual function which aim to incorporate elements of cognitive function — such as the Useful Field of View test (Matas, Nettelbeck, & Burns, 2014; Joanne M Wood & Owsley, 2014) — are somewhat correlated with driver safety (Clay et al., 2005; Cross et al., 2009; Mathias and Lucas, 2009 but see Anstey et al., 2017), but before being taken up by licensing authorities there needs to be evidence that such tests can reliably predict accident involvement prospectively (rather than retrospectively; (Joanne M Wood & Owsley, 2014)).

On-road Driving — The "Gold Standard" measure

Whilst a variety of tests can be used to inform decisions about whether to revoke a driving licence (Anstey et al., 2016; Hird et al., 2014; Schultheis & Whipple, 2014), the primary decision-making tool remains in many cases the on-road driving test (Di Stefano & MacDonald, 2012; Dickerson, 2013; Ranchet et al., 2016; Ross et al., 2016). The advantages of real-world driving tests are fairly clear — the driver has to be able to demonstrate safe and appropriate behaviours when navigating real streets, interacting with other vehicles as well as vulnerable road users (Joanne M. Wood, Lacherez, & Tyrrell, 2014; Joanne M. Wood, Marszalek, Carberry, Lacherez, & Collins, 2015), and carry out a variety of tasks such as lane keeping and obeying traffic rules when driving at both fast (motorway) and slow (urban and parking) speeds. On-road tests using standardised driving routes and conditions (such as at a specified time of day), have been shown to have reasonable reliability (Akinwuntan et al., 2003; 2005), but in practice they simply cannot be standardised in the same way as a laboratory test (Akinwuntan, Wachtel, & Rosen, 2012; Di Stefano & MacDonald, 2012). Because of this one of the strengths of the approach (the variety of conditions experienced in the real world) becomes one of the main weaknesses. Some parts of the country will have test routes that are easier to drive than others, and even for a single test site there will be huge variation depending on factors such as time of day and time of year. Consider the demands of driving in icy conditions, at rush hour on a dark winter's day (poor traction requiring anticipation of other vehicles, many other vehicles, with glare from oncoming traffic meaning there are poor visual signals about the environment and other road users) compared to the same route on a dry, sunny day on the weekend when there is less traffic. This variation could lead to an individual driving at the required standard simply because they experience less demanding conditions, and as a result they cope with their deficits. In contrast, road conditions with greater perceptual, motor and/or cognitive demands could have exposed the limits of the compensatory strategies being used (e.g. Raw, Kountouriotis, Mon-Williams, & Wilkie, 2012) and highlighted conditions under which driving safety would not meet the required level to retain a driving licence.

Such heterogeneity in driver capabilities is not well captured by on-road tests, which can only give fairly crude categorical outcome assessments (Hird et al., 2014; Ranchet et al., 2016). These non-parametric, observational measures lack the subtlety to monitor different elements of driver skill (e.g. Cuenen et al., 2016) and lack the sensitivity to monitor subtle fluctuations in driving performance which may have important diagnostic potential (e.g. Bunce, Young, Blane, & Khugputh, 2012).

Measuring Perception, Action and Cognition using Driving Simulators

It seems then that pure tests of visual function cannot adequately capture all deficits that impair driving (and indeed could capture visual deficits that have no clear impact upon driving). At the other end of the spectrum on-road driving tests have strong ecological-validity, but have various weaknesses, including lacking the control and reproducibility of lab-based tests. There is, therefore, a clear need for an intermediate form of measurement; one that is both reliable/reproducible whilst also tapping into more than just basic visual functions. Computer simulated driving environments (driving simulators) would seem to fulfil these needs, providing a flexible way of generating a range of visual display conditions that can place demands on the same perceptual-motor and cognitive functions as real-world driving (Akinwuntan et al., 2012; Classen & Brooks, 2014; Lees, Cosman, Lee, & Fricke, 2010; Mayhew et al., 2011), however the use of simulation in practice is sparse (Dickerson, 2013). Whilst in recent years many studies have supported the use of simulators as a form of driving assessment (Bédard et al., 2010; Casutt, Martin, Keller, & Jäncke, 2014; Classen & Brooks, 2014; Eramudugolla, Price, Chopra, Li, & Anstey, 2016; Mayhew et al., 2011; Shechtman, Classen, Awadzi, & Mann, 2009); see Dickerson, 2014 for a review), the tasks used have largely aimed to reproduce real-world scenarios and assessment methods (e.g. Bédard et al., 2010; Eramudugolla et al., 2016). Matching simulated driving with real-world driving performance can be an important step in establishing validity of these methods for licensing authorities, however, we would contend that the main strength of simulators is not reproducing identical conditions to real driving. Without a great deal of care such uncontrolled tasks will merely lead to similar limitations as possessed by real-world driving tests (namely lack of control over conditions making interpretation of driving errors/ behaviours difficult) whilst failing to exploit the various benefits of using simulation to assess specific aspects of driving skill.

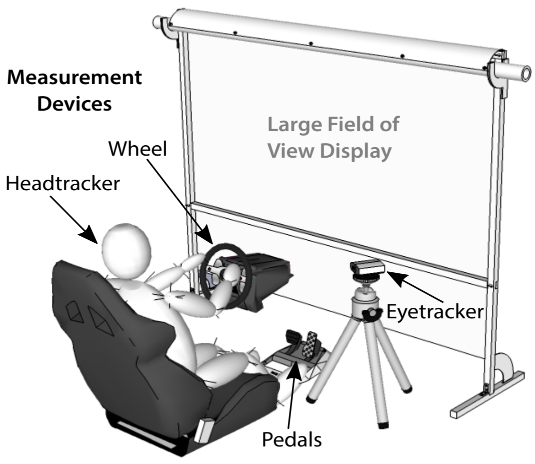

Figure 1: *Components of an intermediate-level driving simulator (such as the one used in Raw et al., 2012, and Smith et al., 2015).*

Of course the term "driving simulator" can be used to describe a wide variety of experimental tools consisting of a visual display and devices for measuring motor behaviour (Figure 1). These range from a simple desktop computer and monitor with a joystick attachment, to fixed-based simulators with large field-of-view displays (Figure 2A), through to an actual car mounted on a large bespoke motion-base platform (like the University of Leeds Driving Simulator; G. K. Kountouriotis and Merat, 2016; Figure 2B). The precise form of the required driving simulation will vary depending on the need of the tester and the likely deficits of the testee: from testing steering control on an empty road (Raw et al., 2012; Figure 3A), through to full city simulations with vulnerable road users walking through the city (Smith et al., 2015; Figure 4A).

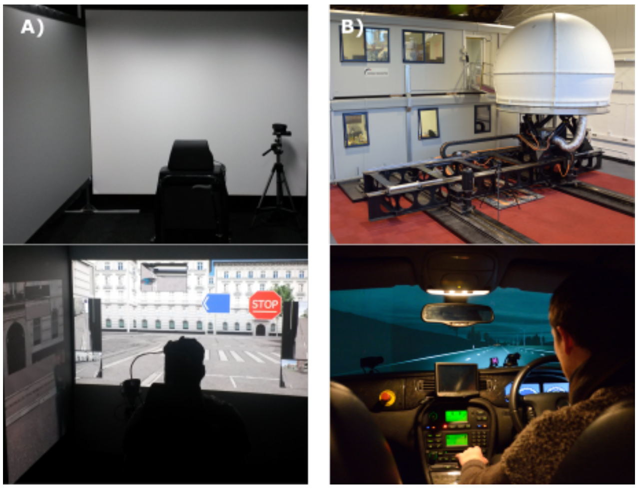

Figure 2: *Images of A) the fixed-base simulator used in Raw et al., 2012 and Smith et al., 2015, and B) the University of Leeds Driving Simulator with a motion-base platform and real car chassis.*

Because of the sheer variety of simulator platforms, it is useful to consider some example methods that have been successfully used to measure particular behaviours related to driving that can differentiate between specific groups[2].

Steering Control

Control of lane position is one aspect of driving which is not captured adequately by observational measures of driving behaviour: it is often scored using a scale ranging from "good" to "bad" (Akinwuntan, Weerdt, et al., 2005; Akinwuntan, De Weerdt, et al., 2005) or via the accumulation of violation points scored by the examiner (Bédard et al., 2008). Such measures may capture extreme errors in position (i.e. veering out of lane) but will not be sensitive to subtle markers of performance that, whilst not resulting in major errors during an on-road test, may indicate general driving difficulties which could limit driving safety in more difficult circumstance (that simply didn't manifest in major errors during the on-road test).

Simulation methods can precisely measure these errors using position-over-time data which enables one to quantify and parameterise lane position, and importantly compare these sensitive measures against a controlled degree of task difficulty. Raw et al., 2012 used this approach to compare a group of older adults to younger counterparts when steering along "virtual" winding roads. To test the capabilities of drivers the road width and vehicle speed were controlled and varied to adjust the task difficulty (changing the spatial and temporal constraints). Varying the task constraints alters the possibility for adopting different steering strategies. Thus, the most constrained (and difficult) steering task was during trials with a narrow road (1.5 m) and fast locomotor speed ($\approx$ 58 km/h), whereas on wider roads at slower driving speeds the spatial/temporal constraints on the driver were relaxed. Figure 3A shows an older participant in the simulator, steering along a sinusoidal roadway. The scene contains a gravel-textured ground-plane, a horizon line where the ground meets the (blue) sky and a set of (white) road edges (note in greyscale Figure 3A these road edges are somewhat blurred and hard to see, whereas in the actual display the lines clearly contrasted with the ground so when projected onto the 1.98 m wide screen they were clearly visible). The scene displayed is sparse with no scenery, no road junctions and no other road vehicles, but this is by design since the inclusion of such extraneous features merely leads to noise in measurement – increasing the variety of behaviours that are then difficult to attribute to the variables under experimental control (in this case age, vehicle speed, and road width).

Even using such a controlled task one can derive multiple measures relating to steering control. The main reason different measures are needed relates to the reference point used for determining performance. For instance, it is common for the (invisible) road centre to be used as the "ideal" reference from which to calculate steering errors (Wilkie & Wann, 2003). Even with this constraint two measures of error will often be needed to provide an overall picture of performance:

1. *Steering error* is the average distance away from the middle of the road in a particular trial, and indicates the overall error within a trajectory produced by a participant (Figure 3B). It is often calculated using root mean squared error (RMSE) due to the contiguous nature of the steering signal (Wilkie & Wann, 2003), but sometimes simply calculated using the mean unsigned distance from the road centre.
2. *Steering bias* is informative about where on the road individuals are steering (Figure 3C), and is calculated using a signed measure of error, whereby errors towards the outside of the road would be signed as negative ("under-steering") whereas errors towards the inside of the bend would be signed as positive ("over-steering"). Steering biases are related to but distinct from steering errors, since it is possible to produce zero steering bias whilst exhibiting large steering error (e.g. oscillating from one side of the road to the other).

These two measures taken together can provide a useful picture of steering behaviour with respect to two references — the middle of the road, and the direction of the bend. Figure 3B shows "steering error" (RMSE) for young (filled symbols) and old (open symbols) groups on narrow or wide roads at fast or slow speeds (adapted from Raw et al., 2012). This measure identifies differences in steering across two road widths and two driving speeds, however the older adults seem to perform fairly well (similar to the young) except for during fast, narrow conditions where they are further away from the middle of the road than the young. "Steering bias" (Figure 3C) provides further information since it shows that whereas younger adults are cutting corners, older adults are overall managing steering errors by maintaining an average road position closer to the road centre.

Whilst subtle differences in driver capabilities can be assessed using these measures at a level of detail not afforded by observational methods, in some cases it may be unclear how these outcome variables translate to driver safety. To use these two measures most effectively requires a task instruction to stay as near to the middle of the road as possible (e.g. "try to steer in the middle of the road whilst steering as smoothly and accurately

[2]These examples were obtained from a number of different project using the University of Leeds School of Psychology driving simulation facilities and the full methods and data have been published previously (as referenced in the text). The data are presented here in new ways to highlight both the breadth and depth of the various metrics obtained from driving simulation methods.

as possible"; (Wilkie & Wann, 2003)) but on real roads drivers are free to adopt a wide variety of steering strategies whilst still being considered safe (for example, cutting the corner is usually a natural and safe steering behaviour; (Lappi, 2014)). The Raw et al., 2012 paper specifically examined how road position was used as a form of compensation and so did not instruct participants to stay in one particular position (so that changes across varying widths/speeds could be observed). Instead participants were instructed to "stay within the boundaries" of the road (Raw et al., 2012) and so the road edges themselves were a further reference point that could be used to acquire further measures of performance. Figure 3D shows the parametric "Time off Road" measure obtained for each age group across two road widths and two driving speeds. Whilst superficially similar to coarse observational judgements of gross lane deviation, this continuous measure of error distinguished between driving speeds and groups driving on narrow roads — revealing that older drivers spent longer off the road than the young, especially under highly constrained conditions (fast and narrow). In real-world driving leaving the road constitutes a major error and is likely to cause a crash (and result in a failed test), but the conditions simulated here forced drivers to try to control steering when speeds were far higher than they would naturally choose for such narrow lanes. This method therefore tested the extent to which errors were due to driver capability or task difficulty. In this simulated scenario, "time off road" provided a useful parametric way of measuring the capabilities of drivers with respect to tasks running at specific and controlled levels of difficulty.

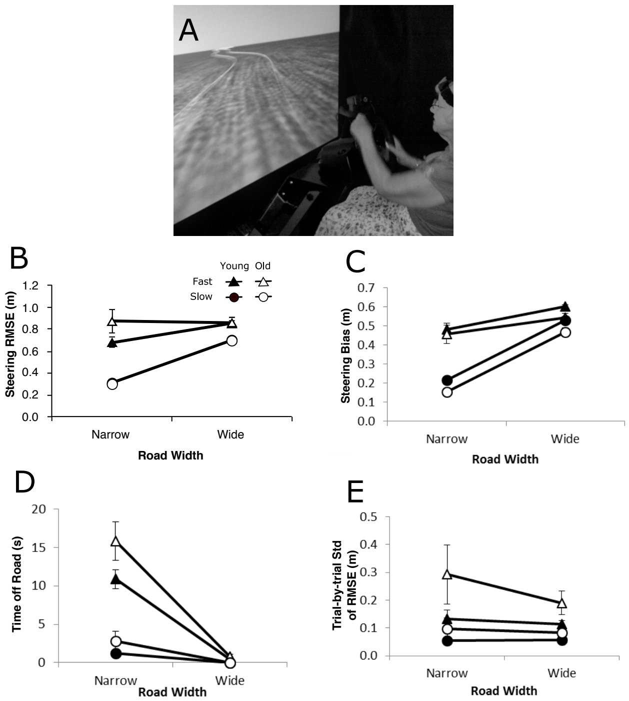

Figure 3: *A) An older driver steering along a sinusoidal road marked by two white road edges, superimposed over a grey gravel-textured ground. Different road widths and locomotor speeds were used to vary task difficulty. Group data were gathered for B) steering error (measured by RMSE), C) steering bias, D) time spent off the road, and E) the standard deviation of steering error for Old (open symbols) and Young (filled symbols) age groups when driving at Fast (triangular symbols) or Slow (circular symbols) speeds along roads of narrow or medium width. Error bars = standard errors. Adapted from* Raw et al., 2012.

A related aspect of behaviour that is apparent in Figure 3D is the change in **Variability** across groups and conditions. Variability is a useful measure of performance because the reference is the average performance of the individual (or group) rather than a particular feature of the environment or task instructions. In principle, a particular individual could produce behaviours that would be captured as errors by the measures mentioned earlier, whilst actually being consistent relative to their own performance (i.e. constant bias). Intra-individual variability has been championed as a possible metric of decline (Bunce et al., 2012) and seems to be related to a variety of other measures of perceptual, motor and cognitive performance (Bauermeister et al., 2016). In Raw et al., 2012 the consistency of performance was calculated using the standard deviation of steering error (RMSE) across trials for each individual within each condition (Figure 3E). This measure showed that older adults were overall less "grooved" in their steering responses than the young, and that they were particularly inconsistent at higher speeds and on narrow roads where the spatiotemporal constraints were high. It is important to note that such measures of variability are simply not available through observational methods. Despite the difference in reference value for Time off Road and Variability (Figure 3D and E) similar patterns across groups and conditions are clear, suggesting that they are both capturing a decline in some fundamental control functions that appear to support consistent and accurate control of steering.

It should be highlighted that the conditions used in this experiment included some that were purposely challenging to examine how group behaviours changed along with spatiotemporal demands, and so were sufficiently taxing to cause even young drivers to make errors. Such conditions are vital for probing the limits of an individual's capabilities, which are not likely to be examined during an on-road test. For instance, at slower speeds on the widest roads it was often difficult to distinguish between younger and older drivers because the lower constraints meant that older drivers were able to adequately compensate, but when constraints were higher (faster speeds and narrower roads) differences between young and older drivers emerged (Raw et al., 2012). A further advantage of parametric measures of this type is that they will be sensitive to small improvements over time (e.g. due to rehabilitation or training) and so can provide useful and encouraging feedback for individuals or instructors about change in function (and performance).

Hazard Detection

The previous section highlighted the utility of using simplified displays and specific tasks to gain precise measures of steering performance relative to a set of predefined reference points. Once the fundamental ability to control steering has been established the natural next step is to use simulators to test the ability of the driver to detect (and avoid) hazards (whilst also maintaining control over steering). Hazard detection is very difficult to assess in naturalistic circumstances since hazards are difficult to quantify and often do not require an overt response. Policy-makers have turned to video-based tests, where individuals passively view real-world footage and are required to respond when a hazard is observed (Grayson & Sexton, 2002). There is growing evidence that performance scores from video-based hazard perception tests are associated with level of crash involvement (Horswill, Hill, & Wetton, 2015), and can distinguish between broad groups of drivers, such as novices or experienced drivers (for reviews see Horswill, 2016a; 2016b.

Whilst video-based tests are easy to administer and can discriminate between large groups there are some issues with using video-based tests for individual road safety assessments with older drivers. The first major issue is that participants are not *actively* in control of the vehicle during these tests. During passive viewing of a scene, individuals are free to adopt a wide range of visual search strategies. When driving, however, visual search patterns are constrained by the need to sample information from straight-ahead in order to anticipate future steering requirements (Lehtonen, Lappi, Kotkanen, & Summala, 2013;

Mackenzie & Harris, 2015; Wilkie et al., 2008)) which could slow responses to potential hazards (especially hazards appearing in the periphery). It is sometimes the case that differences in driving capabilities do not emerge until conditions are taxing and constrained (Raw et al., 2012). Passive video-based tests therefore do not capture hazard detection in the real-world, which requires intact capabilities performing a successful trade-off between the need to scan widely for hazards and the need to sample information for steering control.

A particular example where driving simulation provides an advantage over video is the ability to have greater control over the location and nature of hazards. For example, a driver with visual field loss may struggle to respond to hazards in specific regions of their visual field when driving, but may perform adequately during video-based test if hazards do not fall solely within the affected field. This can be contrasted with another driver with visual field loss who usually compensates for their deficit using eye and head movements to sample from across the scene — because videos are recorded from a fixed position they do not dynamically change in response to the gaze of the driver and have limited field of view, so the driver may fail to detect hazards during the video based test that they would detect without problems when actually driving. This highlights how difficult it is to ensure that video tests are optically correct with respect to the view of the participant. For example, correct perspective (i.e. the geometric layout of objects in the scene corresponding to the participant's viewing position) requires the camera position in the recorded video to match the participant's individual eye-height and field of view. Without this correction it is unclear how the "field" of the video matches to the visual field of the participant (which is especially problematic when interpreting hazard detection in patients with visual field deficits). In contrast to video-based tests, simulation methods allow for hazards to be presented in an optically-controlled manner with respect to the participant's current viewpoint, so a driver's ability to respond to hazards in specific locations can be more systematically assessed. Smith et al., 2015 used simulation to generate a dynamic visual environment in order to test the ability of drivers to detect vulnerable road users in an urban driving environment. These methods were used to test a group of healthy older adults compared to age-matched counterparts that had visual field loss caused by a stroke (homonymous hemianopia, HH). Here the driving task was carried out at a fixed speed (to avoid some individuals driving more slowly than others, e.g. (Bromberg, Oron-Gilad, Ronen, Borowsky, & Parmet, 2012), but otherwise the steering trajectories and lane positioning were fairly unconstrained (certainly compared to the Raw et al., 2012 and the environment was rich, comprising multiple lanes, sign-posts directing the driver at each junction, pavements for pedestrians to walk along, and buildings and other road furniture to define the overall layout of the environment. This visual environment allowed the pedestrians to be embedded in the world in a realistic fashion. Rather than focussing on driving performance per se, the primary test here was of the capabilities of drivers spotting pedestrians in the scene, and identifying whether they were walking perpendicular or parallel to the road (i.e. more or less likely to be a hazard). The pedestrian detection task was essentially a choice reaction time measure, leading to two key metrics: correct detection (Figure 4B; identifying that the pedestrian had appeared, and also the direction they were walking) and reaction time for correct detection (Figure 4C).

These measures usefully identified differences between conditions (slower RTs when driving) and the groups (reduced correct detection and slower detection by the HH group). During our analyses we were particularly interested in seeing whether some individuals were able to compensate for large field deficits when driving. We felt that it was particularly important to note that one individual with a left hemianopia performed, on average, better than many in the control group, but failed to detect one hazard (presumably because the pedestrian appeared in the affected visual field). Not only does this highlight the importance of testing specific functional areas that are likely to be affected by the deficits of the target population, but also the likely limitations of real-world testing whereby it is possible for certain areas to remain untested (OECD, 2001, p 81–91).

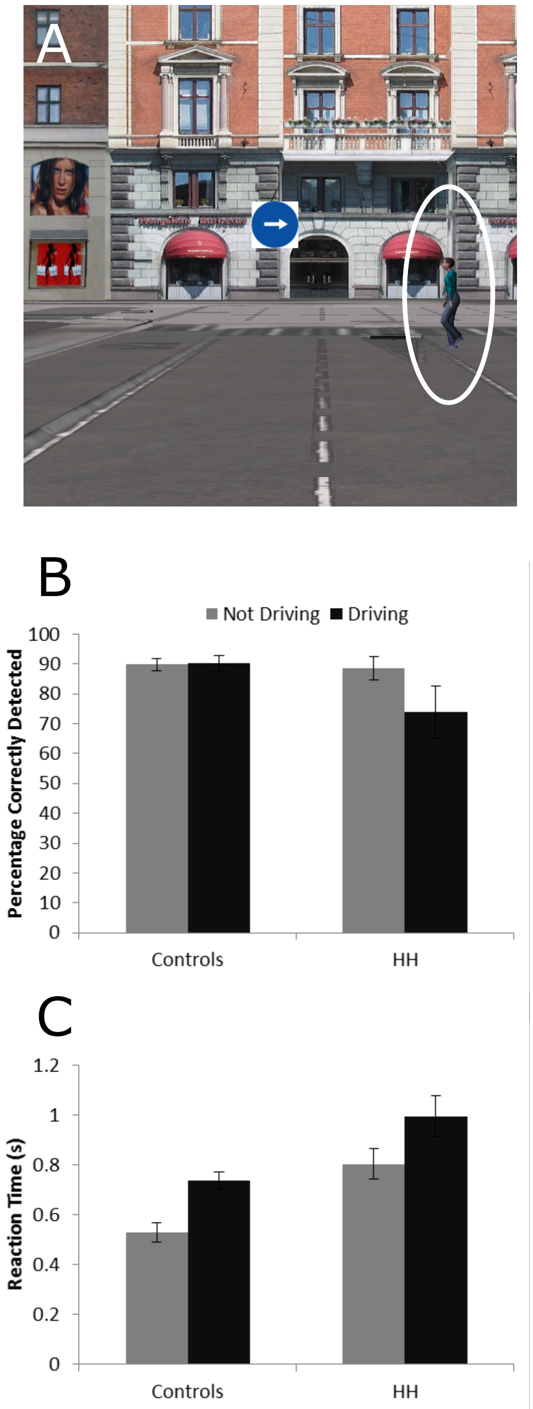

Figure 4: *A) The simulated urban driving environment for a participant navigating and detecting the appearance of pedestrians. B) The percent correct and C) the reaction time to detect pedestrians for groups with visual field loss (HH) or age-matched Controls, either in a control condition when they were responding to the appearance of a pedestrian (Not Driving) or when driving and navigating through the town and also having to respond to pedestrians (Driving). Panel B) shows the proportion of pedestrians identified with the correct response indicating that the driver had determined their direction of travel, whereas panel C) gives the reaction times for when responses were correct. Error bars represent standard error of the mean. Adapted from Smith et al., 2015.*

The Future of Driving Assessment

The examples provided in the previous sections highlight how driving simulators allow for both control and flexibility over tests which could be used to augment current driving assessment methods, allowing for more detailed and sophisticated individual assessments. The strength of driving simulation methods comes from isolating the core components of driving to ensure that each is tested and intact function is demonstrated. This provides a much richer understanding of the capabilities (and limitations) of each individual driver and the extent to which driving difficulties can be attributed to perceptual, motor and/or cognitive problems.

It should be made clear that we do not propose that driving simulators be designed to replace on-road tests. Rather, driving simulators would be most powerful when used as an intermediary step. Figure 5 shows an example testing battery that covers core components of driving, divided into those carried out purely on visual function, a series of tests carried out in simulators, followed by an on-road test. The actual implementation of such a system would depend on the resources available to the local administrative body. The cost of the required simulation will vary across targeted tasks, for example lane keeping and error correction can be assessed with smaller field of view displays and less sophisticated simulation environments compared to the requirements for dual-task tests (such as pedestrian detection). In an ideal world (without resources limitations) *all* tests would be carried out with *all* individuals returning to driving (e.g. post stroke) or regularly with older adults past a threshold age. Pragmatics (in terms of time costs for the individual being tested and the financial cost of performing each test) will mean that tests are likely to be triaged, so that only those passing earlier stages of the perceptual-motor function tests would be recommended for later tests, with the final on-road test only being made available once previous stages are passed (Figure 5). Of course, one issue that is raised by having improved measures of performance is determining what reference value for an individual indicates that they are capable of driving. The measured performance value can be compared against the distribution of the population and thresholds identified based on a predetermined cut-off (e.g. the bottom 1%). But such cut-offs tend to be arbitrary and may have a weak relationship with any improvement of overall road safety (OECD, 2001, p 81-91). Ultimately the cut-off will need to be decided based on the resources available for on-road testing as well as the degree of risk the licencing authority (as dictated by society) is willing to accept.

One live issue that is still under investigation is the degree to which driving simulations should attempt to match particular real-world driving conditions. The perspective put forward in this manuscript is that the main strength of simulators is to create specific scenarios that match the key informational variables of particular conditions rather than attempting to make a general simulation that attempts to reproduce all aspects of real-world driving. The reason for this is twofold: i) it is impossible to accurately reproduce every perceptual signal produced across all driving conditions (simply consider the difficulties involved with producing accurate glare from oncoming vehicle lights at night, and the different requirements needed for generating daytime lighting conditions); ii) simulations that try to recreate all components of real driving will merely lead to the same measurement problems as experienced by on-road testing (as outlined earlier). This paper describes two types of simulated setting that did not target global "realism", rather the experiments were designed to provide key relevant sources of perceptual information and take measurements of motoric behaviours produced in response to this information (see Figure 1). The first setting (Raw et al., 2012) used a fairly sparse display with no scenery, no road junctions and no other road vehicles in an attempt to remove extraneous features, in order to reliably measure steering control. The second setting (Smith et al., 2015) could be considered more "realistic" than the steering control conditions (because of the buildings, pavements and other environmental objects), but this task actually required very little steering from participants (so would not have been suitable for getting robust steering measures). The rationale for choosing this latter environment was the need to create a visual environment that allowed visual objects (akin to pedestrians) to be embedded in the world in a way that matched the position and optical characteristics of vulnerable road users walking next to and crossing actual roads.

Related to the issue outlined above is a common challenge associated with the use of driving simulators – namely the extent to which participants experience motion-sickness. It is an inconvenient truth that humans experience motion-sickness resulting from a wide variety of conditions where the usual relationship between visual and non-visual (e.g. vestibular) signals has been altered (Keshavarz, Riecke, Hettinger, & Campos, 2015), hence sea-sickness, car-sickness, air-sickness and simulator-sickness are all well-known and fairly common phenomena. There are large individual differences in susceptibility to motion-sickness across the population, but there are various factors that can increase the likelihood of feeling sick, not least an increase in age (Brooks et al., 2010). Whilst it is beyond the scope of this present manuscript to provide a detailed examination of the underlying causes of motion sickness (and all the various methods that are able to reduce sickness; for a review see Keshavarz et al., 2015 we highlight here the approaches used during the reported experiments to minimise sickness (admittedly with mixed results). When simulating self-motion we ensure that we keep the testing laboratory at a cool temperature (using air conditioning and/or fans), and where possible we have the participant in active control of the simulated vehicle. We also avoid long testing sessions without rest breaks, and where we think there are particular reasons to expect motion sickness (i.e. older participants) we will sometimes use displays of smaller extent and also reduce the amount of rotation and acceleration produced in the visual displays (i.e. by creating roads that with larger radius bends whilst keeping the vehicle speed fairly constant). Many of these methods map onto our recommendations for creating simulations that are as controlled and targeted as possible.

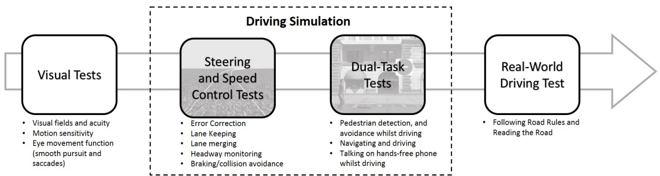

Figure 5: *An example battery of tests which could be used for sophisticated individual assessment of fitness to drive. From left-right the phases of assessment increase in the level of complexity and level of correspondence to unconstrained real-world driving. Suggested skills which could be targeted at each phase are bullet-pointed. For example, "Lane Keeping" and "Pedestrian Detection" could be assessed with tasks similar to those in Raw et al., 2012 and Smith et al., 2015 respectively.*

Whilst there appears to be a clear role for simulation as part of future driving assessments, the utility of these techniques can be much broader than simply deciding who is eligible to retain a licence. Reliable measurement is the starting point for providing richer feedback to the individuals being tested. Indeed, there is no reason why the assessment methods can't be used as part of the training and feedback process in concert with rehabilitation services (e.g. for those post-stroke; (Akinwuntan, Weerdt, et al., 2005; Akinwuntan et al., 2012)). There are continuing efforts to improve rehabilitation methods that enhance recovery of function and we can only hope that advances in medical techniques lead to greater recovery for more individuals. In this context having a sensitive measure of the underlying components of driving will be critical for providing the necessary feedback about recovery to individuals. For those who are having their licence revoked the ramifications in terms of mobility and quality of life can be huge (Edwards et al., 2009), so it is essential to get "buy in" on the decisions being made about their capabilities. After a stroke an individual may not be able to accurately assess their own driving ability (McKay, Rapport, Bryer, & Casey, 2011; Patomella, Kottorp, & Tham, 2008; Scott et al., 2009), and feedback about capabilities could be a crucial component for encouraging mobility in those with the requisite functions. Of course, some will not be able to regain sufficient function, so should be precluded from holding a driving licence. Ideally driving cessation occurs with the consent of the individual but some of the most difficult to convince about driving restrictions are individuals with little/no insight as to their own deficits. It can be difficult to persuade an individual that failing to see a certain number of abstract items in a field test is linked to their driving performance, whereas being able to inform an individual about the number of (virtual) pedestrians they failed to detect during a simulated drive is a much more powerful and convincing message to deliver.

There are many exciting possibilities using simulation techniques to help drivers, instructors and assessors in improving and maintaining standards of driving. Simulators can be used by novices learning to drive for the first time, older adults having a "refresher course", as well as experienced drivers returning to driving after injury. They can be used by non-professional drivers but also professionals who require higher standards of performance for various functions (including vision). Specific scenarios can be targeted to give repeated practice of difficult or dangerous manoeuvres, and are ideal for increasing the confidence of a driver experiencing conditions such as getting up to speed and merging with motorway traffic (a problematic situation for older drivers; (de Waard, Dijksterhuis, & Brookhuis, 2009)). In many other professional fields "simulator time" is logged and contributes towards the final assessment goals for gaining/retaining a licence (e.g. a pilot's licence; (Allerton, 2010)) and there is huge scope to expand this practice into the domain of driving. One counter-argument against increased use of simulation for training/assessment is that perhaps in the future cars will no longer need drivers. There are major advances underway in the design of vehicles, with many companies planning on producing automated cars in the next 5–10 years (Business Insider Intelligence, 2016). Whilst there may be futuristic claims that the roads will soon be filled with "self-driving" cars, there is broad agreement that it is unlikely that automation will replace human drivers anytime soon. The "open" nature of current road infrastructure (which will include a wide variety of vehicles for decades to come) means that complete vehicle autonomy is a real challenge. Automated vehicles, however, could provide additional support for drivers with various forms of visual (or other functional) decline. In this context it is even more crucial to improve assessment methods of drivers to better understand both their individual capabilities and weaknesses so cars can be better designed to support safety and mobility for all.

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