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Movement control in older adults: does old age mean middle of the road?

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Old age is associated with poorer movement skill as indexed by reduced speed and accuracy. Nevertheless, reductions in speed and accuracy can also reflect compensation as well as deficit. We used a manual tracing and a driving task to identify generalised spatial and temporal compensations and deficits associated with old age. In Experiment 1 participants used a hand-held stylus to trace a path. In Experiment 2 participants steered along paths in a virtual reality driving simulator. In both experiments, participants were required to stay within the boundaries whilst we manipulated task difficulty by changing path width or movement speed. The older group showed worse performance in the highly constrained conditions. Corner-cutting effectively reduces the curvature of bends but yields a greater risk of error (i.e. clipping the path/road-edge). Corner-cutting is thus less risky on wider paths and we found that corner-cutting increased for both age-groups in both tasks when paths were wider. Crucially, we observed a greater degree of corner-cutting in the young group compared to the old, suggesting the old group compensated for decreased motor skill with 'middle-of-the-road' behaviour. Enforcing increased speed caused all participants to increase corner-cutting. Thus, older participants showed spatial compensation for decreased skill by biasing their position towards the middle of the path in both a manual and steering task. External constraints (narrow paths and fast speeds) prevented this strategy and revealed age-related declines in skills central to manual control and driving.

Keywords: Motor control, compensation, age, steering, locomotion.

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Movement skills deteriorate with age, with movements becoming slower, less accurate and more variable (Schmidt & Lee, 1999). This decline can be explained through changes in physiology including a reduction in sensory sensitivity, deterioration in strength and flexibility and an increased susceptibility to diseases that affect both the central nervous system (e.g. stroke) and the periphery (e.g. arthritis). The impact of these changes is profound, and a decline in motor ability can greatly limit the extent to which older people are capable of undertaking everyday tasks (Giampaoli, Ferrucci, & Cecchi et al., 1999; Rantenen, Guralnik, & Foley et al., 1999). It is not surprising then that older adults show decrements in performance when faced with behavioural tasks that examine movement speed and accuracy in a laboratory environment. For example, in simple motor coordination tasks (which require the execution of fast and repetitive movements within a set time frame), older adults take a longer period of time to achieve the same movement goals as their younger counterparts (Desrosiers, Hebert, Bravo, & Dutil, 1995; Verkerk, Schouten & Oosterhuis, 1990). While aging causes a direct reduction in the speed at which movements can be carried out, it is possible that this age-related slowing is also driven by compensatory processes. Evidence suggests that humans are able to rapidly assess their intrinsic motor variability and optimize their motor strategies (Trommershauser, Gepshtein, Maloney, Landy & Banks, 2005). One strategy is generating slower actions to make it easier to use on-line feedback to make corrective adjustments. An increase in movement duration can, therefore, allow older adults to perform at an equivalent level of spatial accuracy as a younger population, with decrements only becoming apparent when there is an external timing constraint imposed upon the task (Morgan, Phillips & Bradshaw et al., 1994; Welsh, Higgins & Elliot, 2007).

It can be seen that there are two possible interpretations of an increase in movement duration as a function of age: it could be a direct consequence of physiological changes, or a strategic response to these changes. Strategic compensation does not necessarily mean that behaviour is adjusted through conscious control. Older adults may consciously attempt to compensate for their difficulties and/or adapt to increased signal variability in a cognitively impenetrable manner (Desrosiers et al., 1995; Krampe, 2002; Smith, Umberger & Manning et al., 1999; Verkerk, Schouten & Oosterhuis, 1990).

When it comes to interpreting motor control performance in a laboratory or clinical environment, practical issues arise. In a motor control task it can be difficult to detect changes in movement as a function of age when spatial accuracy is used as a measure, unless task duration is carefully controlled (i.e. participants may slow down to preserve accuracy). Furthermore, in rehabilitation settings, encouraging an individual to speed up their movements might actually interfere with their own successful strategic compensation.

Accordingly, it can be seen that there are good scientific and clinical reasons for understanding both the quantitative and qualitative changes that occur in movement as a function of age. Thus, the aim of our experiments was to explore whether older adults make spatial *and* temporal adjustments to their movements in order to meet the demands of different skilled motor tasks.

The relationship between movement speed and accuracy was first formally defined by Fitts (1954). Fitts proposed that the time taken to complete a movement is a function of movement amplitude and target size. The relationship between duration and task parameters has been examined extensively within the movement literature (see Plamondon and Alimi, 1997 for a comprehensive review) and it has been established beyond a doubt that increasing accuracy demands (e.g. by decreasing target size) produces a lawful increase in movement duration – the so-called 'speed-accuracy trade-off'. We wanted to determine whether there are general strategies used to compensate for age-related deficits, so we examined the relationship between speed and accuracy in two different motor control tasks. Previous comparisons of hand-writing and walking movements have demonstrated that there are general patterns of behaviour that emerge during both actions (Hicheur, Vielledent, Richardson, Flash & Berthoz, 2005). Moving the hand to trace a path has the classic characteristics required to examine speed-accuracy trade-offs as well as strategic compensation (Johnson, Culmer, Burke, Mon-Williams & Wilkie, 2010). Visual feedback about hand position relative to the path edge can allow an individual to stay within a wide path when moving slowly. If the accuracy demands are increased (i.e. the path becomes narrower) then speed should reduce, or if the speed is increased then accuracy should be impaired. If there is increased visual-motor variability with age then we should also expect older adults to produce slower speeds and/or the adoption of movements that trace closer to the path centre (to avoid leaving the path). Similar issues arise during locomotion along demarked pathways. Steering smoothly and accurately around a bending roadway requires the same considerations of visual-motor variability as tracing with the hand. Cutting the corner allows the driver to take a faster line through the bend, but it also exposes the driver to increased risk of crossing the road boundary and having an accident. While many experiments have examined the information used to control steering along curved roadways (Land & Horwood, 1995; Wilkie & Wann, 2003; Salvucci & Gray, 2004; Coutton-Jean, Mestre, Goullon & Bootsma, 2009; Wilkie, Kountouriotis, Merat & Wann, 2010) as well as the neural basis of this control (Field, Wilkie & Wann, 2007; Billington, Field, Wilkie & Wann, 2010) it remains unclear whether there are systematic changes in steering behaviour based upon the variability of the driver. If there are general compensatory mechanisms employed by the central nervous system then we would expect to see them exhibited when visual-motor variability increases with age.

In the first experiment we used a manual task in which participants were asked to trace paths of variable thickness. In two of the conditions, speed was controlled (using a set fast or slow speed dictated by a moving 'window'), which allowed us to examine spatial strategies under a temporal constraint. We also included a condition in which participants were able to move at an unconstrained speed in order to explore natural age differences in speed-accuracy selection (and trade-off). The participants were instructed that their trajectory must not leave the delineated path and, when time was unrestricted, that they must complete the task as quickly as possible. We used one path that was sufficiently thin to ensure that the task had to be completed by tracing the path's shape exactly, but we also included two thicker paths where the finish point could be reached faster in the preferred speed condition by cutting-the-corners. Because this corner-cutting strategy risks error (i.e. leaving the path), it would be safer to take longer in the preferred speed condition, and stick to the middle of the path. In light of the increased motor variability associated with older age, we therefore expected that when older participants were pacing themselves, they would stay closer to the middle of the path to reduce the risk of crossing outside of the path boundary. On the other hand, we expected less variable younger adults to cut-the-corners in order to reach the finish-line in a shorter period of time. We were also interested to determine whether any age difference in spatial strategy would remain when movement duration was pre-set (i.e. would participants still cut-the-corners when they could not achieve shorter overall movement duration?).

In the second experiment we aimed to identify whether spatial compensation would translate to a different skilled movement scenario: steering along a roadway. We used the same shaped path as featured in the first experiment to create a series of virtual roads within a simulated driving environment. We chose steering as a comparison movement for three reasons. First, driving plays an important part in an older person's ability to maintain independence in later life, and therefore an increased awareness of age differences in steering behaviours has broad implications. Second, accident statistics suggest that older people are involved in a higher number of fatal incidences per 100 miles driven when compared to younger drivers (Massie, Campbell & Williams, 1995)[1]. Thus, identifying the strategies adopted by older drivers may help in understanding road-safety issues. Finally, a

[1] The underlying cause of road accidents is not always clear but the most frequent class of crash where an older driver (>60 years) was considered partly to blame were 'right of way violations'; carrying out manoeuvres such as lane changes, or turning on or off a road (Clarke, Ward, Truman & Bartle, DfT Road Safety Research Report 109, 2009).

simulated driving task provides the benefit of studying movement in a realistic scenario, while at the same time allowing us to maintain precise control over the visual stimuli. We measured steering bias (i.e. the extent to which participants cut-the-corner) and steering variability as participants steered along a series of roads that varied in width at slow or fast speeds. Similar studies conducted in the past with younger adults have identified a tendency to "cut-the-corner" and therefore steer closer to the inside road-edge (i.e. take the so-called 'racing line') (Mars, 2008; Robertshaw & Wilkie, 2008). Nevertheless, maintaining a more central road position would allow an older driver with increased motor variability to contain his or her trajectory within the constraints of the road boundaries. Hence, we predicted that where possible older participants would be more inclined to adopt a 'middle-of-the-road' strategy and exhibit less corner-cutting than the younger population. When external constraints (high speed) make a 'middle-of-the-road' compensatory strategy difficult to implement we expected errors in the older participants to increase.

Experiment 1

Method

Participants

Twenty seven healthy individuals with no history of ophthalmological or neurological problems were tested from an opportunistic sample. All participants were right-handed as indexed by the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) with an average score of 90.26 (*SD* = 13.88) out of the maximum 100. Participants were split into two groups. One young participant was excluded because their RMS error scores exceeded the group mean by over 3 *SD*. After exclusion, the 'young' group consisted of 13 participants (6 females, 7 males) aged between 18 and 38 years (average age = 27.69, *SD* = 6.06). The 'old' group comprised 13 people (11 females, 2 males) aged between 62 and 80 years (average age = 69.62 years, *SD* = 5.39). The University of Leeds ethics and research committee approved this study and all participants gave written informed consent in accordance with the Declaration of Helsinki.

Procedure and Apparatus

A tracing task was created using 'KineLab', a kinematic assessment tool that can be used to design visual-spatial tasks and record the x and y co-ordinates of hand movement (Culmer, Levesley, Mon-Williams & Williams, 2009). In this experiment, participants used a handheld stylus to draw along paths presented on a tablet PC. Each path was the same shape (measuring 184.3 mm in height from top to bottom, and 19.8 mm in width from left to right), but varied in thickness (2 mm, 4 mm, 6 mm). The speed at which participants were required to trace also varied between trials. Two of the conditions were set at a constant speed whereby the path was presented within a moving 'window' which moved along and gradually revealed the future path whilst the path behind disappeared (see Figure 1a). This occurred at a rate of 12.86mm/sec in the slow condition and 23.64 mm/sec in the fast condition. A third condition was also included in which participants were able to trace at their own preferred pace. In this condition the path was static and fully visible throughout the trial (see Figure 1b). Each path thickness (narrow, medium and wide) was presented five times within each of the speed conditions (slow, fast, preferred) resulting in a total of 45 paths to trace (presented in a random order). Participants completed the task using their (preferred) right hand and were provided with the following instructions; "follow the path from start to finish as quickly as possible. You must NOT go outside of the path".

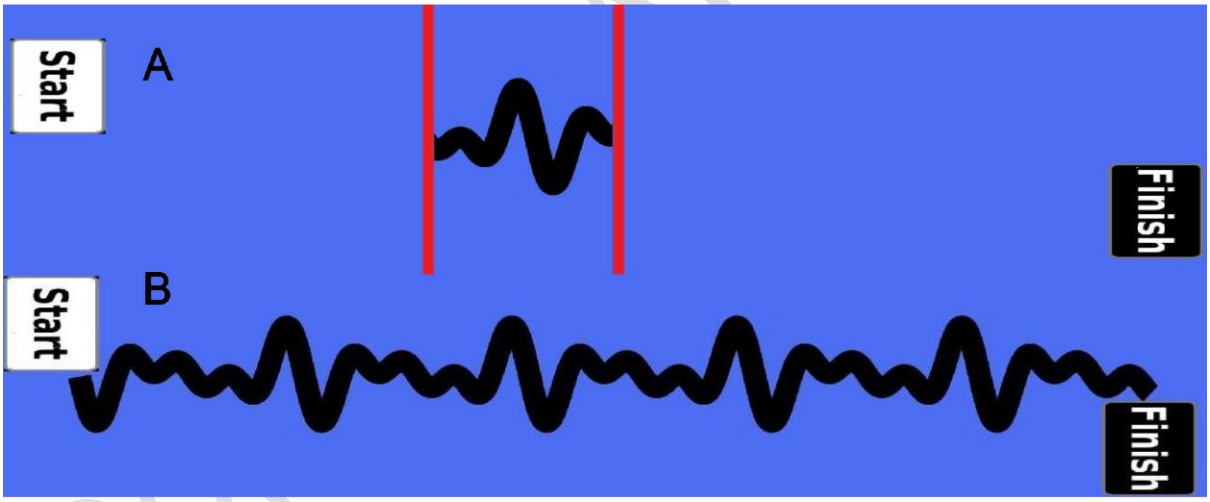

Figure 1. *Screen shots taken from the Kinilab tracing task as the stimuli appeared to participants on the tablet PC screen (Nb. not to scale). (**a**) An example of a set speed trial with the medium path. **(b)** An example of a preferred speed trial with the medium path.*

Analysis

We calculated three measures of tracing performance: (i) Movement Time (MT), the time taken from the moment the stylus exited the start icon until the point at which the stylus crossed into the finish icon, (ii) Path Length (PL), which indicated the extent to which participants cut the corners by recording the length of the trace from start to finish, and (iii) Root Mean Squared (RMS) Error, the average distance of the stylus from the closest reference point on the middle of the path. We calculated each individual's mean score for the three path thickness conditions and the three speed conditions on each measure (MT, PL and RMS error). These data were then input into separate mixed ANOVAs to examine differences between the task conditions and age groups. Greenhouse-Geisser estimates of sphericity (ε) are reported where degrees of freedom have been adjusted.

Results

Figure 2a displays the mean Movement Time (MT) for the young and old groups on the narrow, medium and wide paths, in the controlled slow, controlled fast and preferred speed conditions. The ANOVA revealed significant main effects for path thickness (F (2, 48) = 38.82, $p < .001$, $\eta^2 = .62$, $\varepsilon = .59$) and speed condition (F (2, 48) = 386.58, $p < .001$, $\eta^2 = .94$, $\varepsilon = .52$), and a path thickness × speed interaction (F (4, 96) = 58.99, $p < .001$, $\eta^2 = .71$, $\varepsilon = .32$). While there was no main effect of age (F (1, 24) = 2.65, $p > .05$, $\eta^2 = .10$), nor interactions between age and path thickness (F (2, 48) = .12, $p > .05$, $\eta^2 = .005$), and no 3-way interaction (F (4, 96) = .07, $p > .05$, $\eta^2 = .003$), there was a significant age × speed interaction (F(2, 48) = 6.41, $p < .001$, $\eta^2 = .21$, $\varepsilon = .51$). Figure 2a shows that path thickness did not greatly alter MT when speeds were held constant, but thicker paths did result in shorter MTs during 'preferred' speed trials. Thus, the 'set speed' trials successfully controlled speed, with the old and young participants having the same MTs in slow and fast conditions. The interaction between age and speed results from the 'preferred' speed condition whereby there was a general increase in MT for the old group compared to the young. The lack of interaction between age and path thickness does indicate, however, that MT reduced by a similar amount as paths increased in thickness. In terms of speed/accuracy trade-offs it seems, therefore, that the old adopted slower speeds overall, but did not moderate speed differently compared to the young.

Because MT decreased on wider paths when moving at the preferred speed it seems that participants may have been 'cutting-corners' to reduce the distance the pen needed to travel from start to finish. To confirm corner-cutting behaviour we examined Path Length (PL). The 'ideal' PL was calculated for the centre of the reference path and paths taken were generally shorter than this value (shown by the horizontal dashed line on Figure 2, right-hand panels). For clarity of presentation, the mean PL on the narrow, medium and wide paths, in the set slow, set fast and preferred speed conditions are shown separately for the young group in Figure 2d and for the old group in Figure 2f. The ANOVA for PL revealed a significant main effect of path thickness (F (2, 48) = 307.16, p < .001, η^2 = .93, ε = .58) and speed (F (2, 48) = 6.63, p < .001, η^2 = .22, ε = .69), as well as a path thickness × speed interaction (F (4, 96) = 13.39, p < .001, η^2 = .36, ε = .61). There was no main effect of age (F (1, 24) = .660, p > .05, η^2 = .03), nor interactions between age and speed (F (2, 48) = .13, p > .05, η^2 = .005), and no 3-way interaction (F (4, 96) = 2.05, p > .05, η^2 = .08). However, there was a significant age × path thickness interaction (see Figure 2b and 2h, F (2, 48) = 9.06, p < .001, η^2 = .27, ε = .58).

The general pattern across conditions shows that PL decreased as the path got thicker, indicating that there was a tendency for participants to cut-corners on these paths. Furthermore, PL was reduced when participants were tracing at faster speeds. The path thickness × speed interaction reflects the different gradients of the lines shown in Figures 2d and 2f, whereby different speed conditions were affected to a greater or lesser extent by the path thickness. These differences demonstrate two things: i) while there was little difference in PL between the set fast and slow conditions on narrow paths, PL decreased more for wider paths at fast speeds than at slow (i.e. there was most corner-cutting on wide paths at fast speeds), ii) while there was little difference in PL for the fast and preferred speeds conditions on the wide paths, PL increased more on the narrow paths at preferred speeds than at fast speeds (i.e. there was less corner-cutting on narrow paths at preferred speeds). While the patterns for PL in old and young were similar, the path thickness × age group interaction indicates that older participants were less likely than the young to cut-the-corner as the path got thicker (see Figures 2b & 2h).

An increase in PL could theoretically be explained by more erroneous tracing, rather than tracing the path more accurately. To confirm that the longer trajectories did indeed follow the path more accurately we calculated RMS error – the distance of the pen from the middle of the reference path at each time-point. The mean RMS error for narrow, medium and wide paths, in the set slow, set fast and preferred speed conditions are shown for the young group in Figure 2c and for the old group in Figure 2e. The ANOVA for RMS error revealed a significant main effect of path thickness (F (2, 48) = 224.188, p < .001, η^2 = .82, ε = .75) and speed (F (2, 48) = 114.4, p < .001, η^2 = .83, ε = .64), as well as a path thickness × speed interaction (F (4, 96) = 26.11, p < .001, η^2 = .52, ε = .69). These results confirm that an increase in PL was associated with improved tracing accuracy (reduced RMS error).

The reduced corner-cutting (increased PL) observed in the old when tracing wide paths could be explained by a general preference for accuracy (and hence slower MTs when unconstrained). To determine whether the older adults were more accurate we examined the age-related results from the ANOVA. There was no main effect of age (F (1, 24) = .011, p > .05, η^2 = 0), nor an age × path thickness interaction (F (2, 48) = 2.30, p > .05, η^2 = .09). There was, however, an interaction between age and speed (F (2, 50) = 6.47, p < .01, η^2 = .21), and a 3-way interaction (F (4, 96) = 2.73, p < .05, η^2 = .10). The interactions occur because the older adults were more accurate in only one condition: tracing wide paths at preferred speeds (t(24) = 2.32, p<.05). The young sacrifice accuracy to follow faster trajectories that cut the corners. In all other conditions the older adults were no better that the young (Figure 2g). To determine whether the old had decreased motor skill we compared RMS error on the narrow path at slow speed across age groups since this condition should reflect the greatest possible accuracy: as expected by the interactions the young were better in this condition and stayed significantly closer to the path centre (Figure 2g; t(24) = 2.08, p<.05).

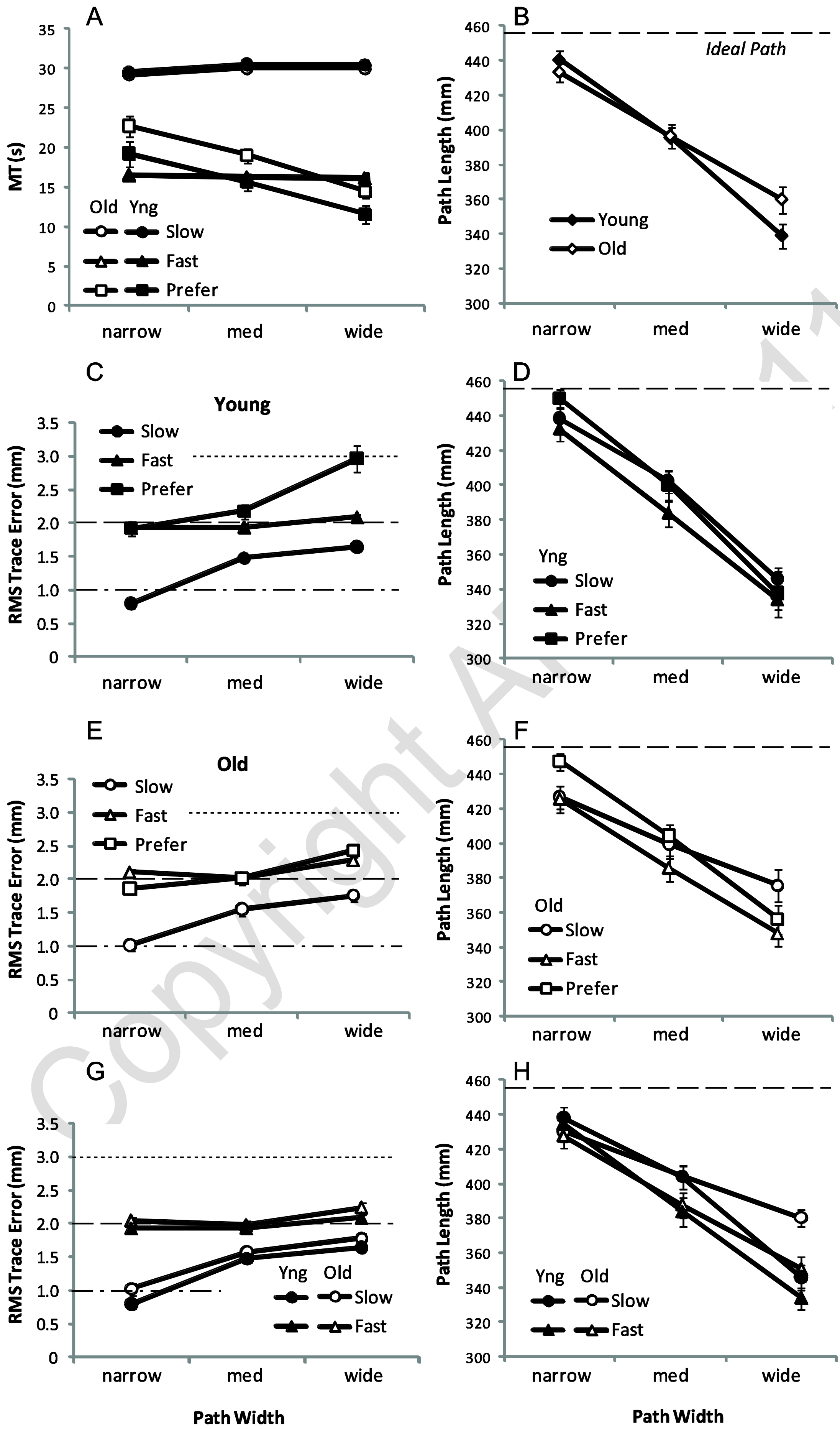
A
MT (s)
Old Yng
Slow
Fast
Prefer
narrow
med
wide
B
Ideal Path
Path Length (mm)
Young
Old
C
Young
RMS Trace Error (mm)
D
Yng
E
Old
F
G
H
Path Width

Figure 2. *Tracing performance on the narrow (2mm), medium (4mm) and wide (6mm) paths at the slow (circles), fast (triangles) and preferred (squares) speeds for the Young (filled symbols) and Old (open symbols) groups:* ***(a)*** *Movement Time,* ***(b)*** *Path Length for the Young and Old averaged across speed conditions,* ***(c)*** *RMS error for the Young,* ***(d)*** *Path Length for the Young,* ***(e)*** *RMS error for the Old,* ***(f)*** *Path Length for the Old,* ***(g)*** *RMS error for the Young and Old for constrained speed conditions,* ***(h)*** *Path Length for the Young and Old for constrained speed conditions. Horizontal dashed lines indicate the 'ideal' path length tracing the path centre (panels B,D,F,H). Horizontal dotted/dashed lines indicate the maximum error (half path width) to stay within the narrow (2mm, dot/dashed line), medium (4mm, dashed line) or wide (6mm, dotted line) paths (panels C, E G). Bars = Standard Error of the Mean.*

Experiment 2

The first experiment demonstrated that, when tracing paths, older adults were less inclined to cut the corners of thicker paths and were less able to accurately trace narrow paths. In the second experiment we examined whether similar patterns of behaviour would be observed in a steering task. As in experiment 1, we varied the path thickness and speed to see whether we could observe age-related changes in behaviour.

Method

Participants

A new group of 28 healthy individuals with no previous history of ophthalmological or neurological problems formed a second opportunistic sample. Participants were split into two groups (*N* = 14): the 'young' group (8 females) were aged between 19 and 39 years (mean = 24.07, *SD* = 5.28) whereas the 'old' group (9 females) were aged between 60 and 84 years (mean = 71.86, *SD* = 7.01). All participants held a UK driving licence and considered themselves to be a driver. The mean EHI score was 86.52 (*SD* = 21.25) indicating that all participants were right-handed. The Addenbrooke's Cognitive Examination Revised (ACE-R) (Mioshi, Dawson, Mitchell, Arnold and Hodges, 2006) was also administered to the older participants to measure basic cognitive ability and the average score was 92.29 out of 100 (*SD* = 6.37). All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

Procedure and Apparatus

Participants were seated in a driving seat placed in front of a large screen (1.98m × 1.43m). The rotating, height adjustable, lockable chair allowed the older participants to comfortably transition into the chair. The distance from the eyes to the screen was 1m, and the distance from the eyes to the ground was 1.05m for all participants (Figure 3).

Figure 3. *An older adult participant steering along a road of medium (3m) width.*

A realistic textured ground plane with superimposed road-edges was presented (similar to Wilkie & Wann, 2003b). The shape of the road (Figure 3a*)* was created using the following sum of sines formula:

$$x = \sin\left(\frac{z}{20}\right) + \sin\left(\frac{z}{15}\right) + \sin\left(\frac{z}{30}\right) \quad (1)$$

The driving task was presented using a PC (Pentium(R) 4 CPU 3.20 GHz) to generate the scenes and a Sanyo Liquid Crystal Projector (PLC-XU58) to back-project the images. The edges of the road appeared in white against a grey gravel textured background with a blue sky (Figure 3). All roads followed the same shape but varied in width: narrow (1.5 m), medium (3 m) or wide (4.5 m). Speed of travel was constant within trials, but varied between trials so that each road type appeared five times at both a slow (8 m/s) and fast (16 m/s) speed. This resulted in a total of 30 roads to negotiate, which took around 10 minutes if the trials were completed without extended pauses. The order of conditions was randomised.

Participants were asked to steer along the virtual road and were told to 'stay within the boundaries'. Steering was controlled using a force-feedback wheel (Logitech G27 with a 'return-to-centre' force active) and a 'paddle' button (positioned beneath their fingers) that allowed participants to control when a trial started (allowing rest between trials if needed). Driving simulators run the risk of inducing motion sickness and this was highlighted to participants during the consent process. Indeed, the majority of the older group did experience some motion sickness with 10 out of the 14 older participants experiencing nausea at some point in the experiment (compared to only 1 of the young group).

Analysis

Three measures of steering performance were calculated: (i) steering error was calculated using the root mean squared (RMS) error of position from the middle of the road for each frame of each trial; (ii) In order to examine the variability across trials we calculated the standard deviation of RMS error (SD of steering error) for each condition; (iii) the steering bias of position relative to the middle of the road indicated whether the participants cut-the-corner or were biased towards the outside edge. Larger positive values indicate more time spent steering towards the inside edge of the bend. A zero value does not, however, indicate that the participant stayed solely on the road midline (e.g. a participant could be highly variable but spend the same amount of time near the outside edge of the road as near the inside edge and so be unbiased). It is therefore important to examine bias alongside RMS error to evaluate steering performance. Trials in which steering error exceeded 4m were treated as outliers and excluded from all analyses, but only five trials needed to be excluded in this way: three trials from the old group and two from the younger group with no more than one trial per participant excluded. Three mixed model ANOVAs were used to explore separately the steering performance measures (steering error, SD of steering error and steering bias). These analyses had a 2 (young and old age groups) × 3 (narrow, medium and wide roads) × 2 (slow and fast speeds) design. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.

Results

Figure 4a displays the RMS steering error for the old and young groups on narrow, medium or wide roads, for slow and fast speed conditions. Table 1 displays the ANOVA results: there was a main effect of locomotor speed (F (1, 26) = 93.06, p < .001, η^2 = .78), road width (F (1,

26) = 41.47, p < .001, η^2 = .62, ε = .77) and a significant speed x width interaction (F (2, 52) = 27.53, p < .001, η^2 = .51). Errors were smallest on narrow roads at slower speeds, but higher speeds caused greater errors when the road was narrow. The age groups performed similarly in most conditions and there was no main effect of age (because of overlap the slow trials for young are hard to see in Figure 4a) but there was a width x speed x age interaction (F (2, 52) = 4.43, p < .05, η^2 = .15). The three way interaction seems to be driven by the reduction in steering error between wide and narrow fast trials in the young (t(13) = 4.89, p<.001) but not for old (t(13) = .15, p=.89).

Table 1. *The effect of road width and locomotor speed on RMS steering error in Old and Young participants in Experiment 2. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.*

	RMS Steering Error				
	F	*df*	η^2	*ε*	*p*
Road Width	41.47	2, 52	.62	.77	<.001 **
Speed	93.06	1, 26	.78		<.001 **
Age[a]	.26	1, 26	.01		.617
Width × Age	2.86	2, 52	.10		.08
Speed × Age	.03	1, 26	.03		.38
Speed × Width	27.54	2, 52	.51		<.001 **
Speed × Width × Age	4.43	2, 52	.15		.02 *

[a]Age was the only between-subjects factor. *Result significant at the p < .05 level.
**Result significant at the p < .001 level.

RMS steering error provides a measure of within trial variability (relative to the road centre). Accurate control of steering depends upon reliably reproducing actions. To examine how consistent the groups were in their steering across trials of the same type we calculated the *SD* of RMS error. Figure 4b displays the mean *SD* of RMS steering error for the old and young groups on narrow, medium or wide roads, in the slow and fast speed conditions. Table 2 displays the ANOVA results in which there were two significant effects. Firstly, there was a main effect of locomotor speed (F (1, 26) = 18.26, p < .001, η^2 = .41), whereby steering was more variable when travelling quickly. This suggests that travelling at twice the speed made maintaining a consistent steering path across trials more difficult. Secondly, the older group were significantly more variable in their steering trajectories than the younger group (F (1, 26) = 6.67, p < .05, η^2 = .20). Notably, the narrow fast condition yielded the greatest difference between the age groups indicating that the older participants found this condition particularly challenging.

Table 2. *The effect of road width and locomotor speed on steering bias and variability in Old and Young participants. Where the Greenhouse-Geisser ε values are reported, the degrees of freedom were adjusted in order to account for sphericity.*

	SD of Steering Error					Steering Bias				
	F	*df*	η^2	*ε*	*p*	*F*	*df*	η^2	*ε*	*p*
Rd Width (RW)	.87	2, 52	.32	.65	.381	214.05	2, 52	.92	.65	<.001 **
Speed (S)	18.26	1, 26	.41		<.001 **	62.23	1, 26	.71		<.001 **
Age[a] (A)	6.67	1, 26	.20		.016 *	6.67	1, 26	.20		.016 *
Width (W) * A	.51	2, 52	.12	.62	.518	.89	2, 52	.06	.65	.378
S * A	1.81	1, 26	.07		.190	.69	1, 26	.03		.415
S * W	.32	2, 52	.03	.68	.379	50.61	2, 52	.70	.64	<.001 **
S * W * A	.45	2, 52	.02	.68	.566	20.82	2, 52	.09	.64	.174

[a]Age was the only between-subjects factor. *Result significant at the p < .05 level.

**Result significant at the p < .001 level

Table 2 also displays the ANOVA results for the steering bias measure. Participants generally cut corners (positive steering bias shown in Figure 4c). Corner-cutting increased on the wider roads (F (2, 52) = 214.05, p < .001, η^2 = .89, ε = .65) and when travelling at the faster speed (F (1, 26) = 62.23, p < .001, η^2 = .71). A significant interaction between road width and locomotor speed (F (2, 52) = 50.61, p < .001, η^2 = .66, ε = .64) showed that the higher speed had a greater influence on steering bias when the road was narrow (Figure 4c). The difference in steering bias between the slow and fast conditions on narrow roads was 0.27 m, whereas on medium and wide roads the difference was 0.13 m and 0.07 m respectively. A significant between-subjects effect of age revealed that the older participants were less likely to cut corners than the young (F (1, 26) = 6.67, p < .05, η^2 = .20). The only exception to this pattern may have been when steering along the narrow road at a fast speed (mean bias for young and old: 0.47 m and 0.48 m respectively) which was when the old struggled to maintain their accuracy (as measured by RMS error) and were also highly variable (shown by *SD* of RMS error).

Looking across the measures it seems that the fast/narrow condition was the most difficult to complete successfully (i.e. by staying on the road) and the old in particular struggled with this speed/width combination. It should also be noted that apart from the fast/narrow condition, the older adults performed at similar levels of RMS error to the young, whilst exhibiting less bias. The old are, therefore, not merely avoiding cutting corners because they value accuracy more highly. It seems that they adopt a more central position in order to stay on the road, which is relatively successful unless the conditions are particularly difficult.

Overall the steering results show that the older participants were more variable in their steering and that corner-cutting was less prevalent. We calculated the length of time participants spent off the road (Figure 4d) and the younger group were consistently able to take 'racing-line' trajectories that passed close to the inside road-edge with no increased risk of leaving the road[2]. We examined this further by plotting individual steering trials for one young (Figure 5b&c) and one old participant (Figure 5d&e). The young participant stayed closer to the middle of the road when travelling slowly on the thinner roads (blue & green lines on Figure 5b) than on the wide road (red lines on Figure 5b), but clearly corner-cutting increased for thinner roads when travelling more quickly (Figure 5c). The older participant showed greater variability in the trajectories taken, especially at the fast speed (Figure 5e), consistent with the measure of *SD* of steering error. But the older participant followed the shape of the road more closely; this is most evident on the wide road at slow speeds (compare the red lines in Figure 5b and 5d).

[2] The same statistical pattern was found for time spent off road as for the other steering measures: a main effect of path width, speed and an interaction between width and speed (respectively F (2, 52) = 63.87, p < .001, ε = .61; F (1, 26) = 64.58, p < .001; F (2, 52) = 45.82, p < .001, ε = .70). The only difference was that the main effect of age did not reach statistical significance (F (1, 26) = 3.52, p = .072).

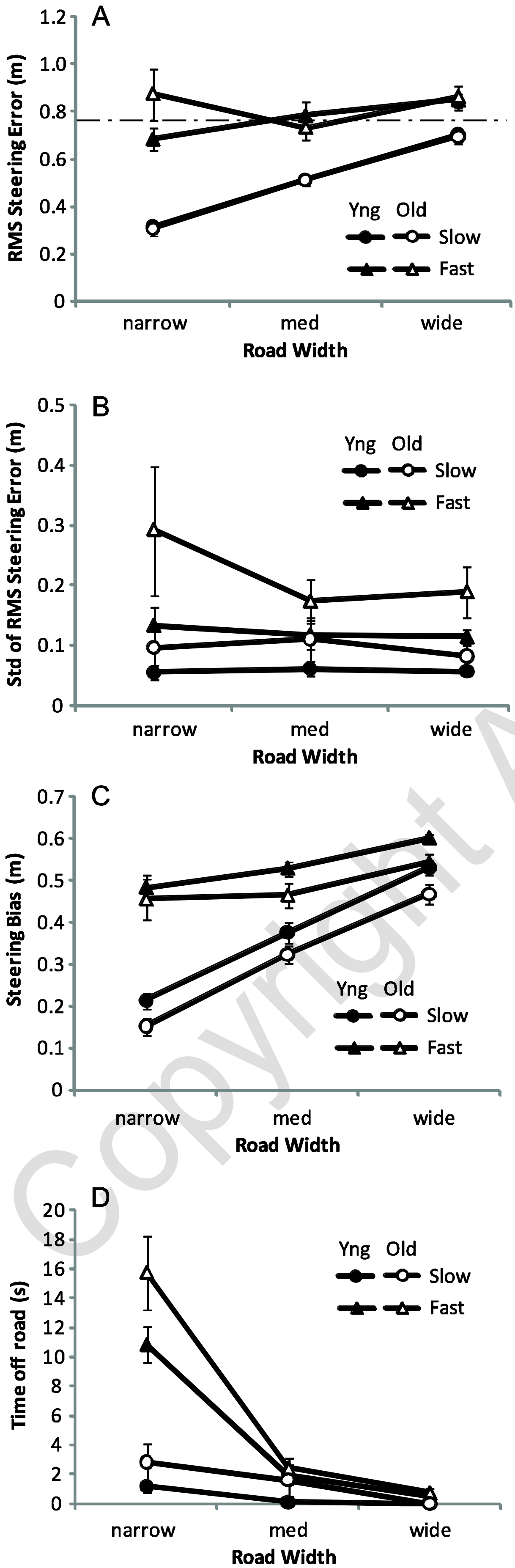
A
RMS Steering Error (m)
1.2
1.0
0.8
0.6
0.4
0.2
0
Yng Old
Slow
Fast
narrow
med
wide
Road Width
B
Std of RMS Steering Error (m)
0.5
0.4
0.3
0.2
0.1
0
Yng Old
Slow
Fast
narrow
med
wide
Road Width
C
Steering Bias (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Yng Old
Slow
Fast
narrow
med
wide
Road Width
D
Time off road (s)
20
18
16
14
12
10
8
6
4
2
0
Yng Old
Slow
Fast
narrow
med
wide
Road Width

Figure 4. *Steering performance on the narrow (1.5m), medium (3.0m) and wide (4.5m) roads at the Slow (circles) and Fast (triangles) speeds for Young (filled symbols) and Old (open symbols) groups:* ***(a)*** *RMS Steering Error, where a larger value indicates that trajectories were further from the path midline**.** The horizontal dot/dashed line indicates the distance of the narrow road edges from the midline (0.75m)* ***(b)*** *Mean SD of RMS Steering Error, where a larger value indicates less consistent steering trajectories across trials**. (c)** Mean Steering Bias, where a larger positive value indicates trajectories passed closer to the inside of each bend.* ***(d)*** *Total time (s) spent off the road in each condition averaged across Young or Old participants. Bars = Standard Error of the Mean.*

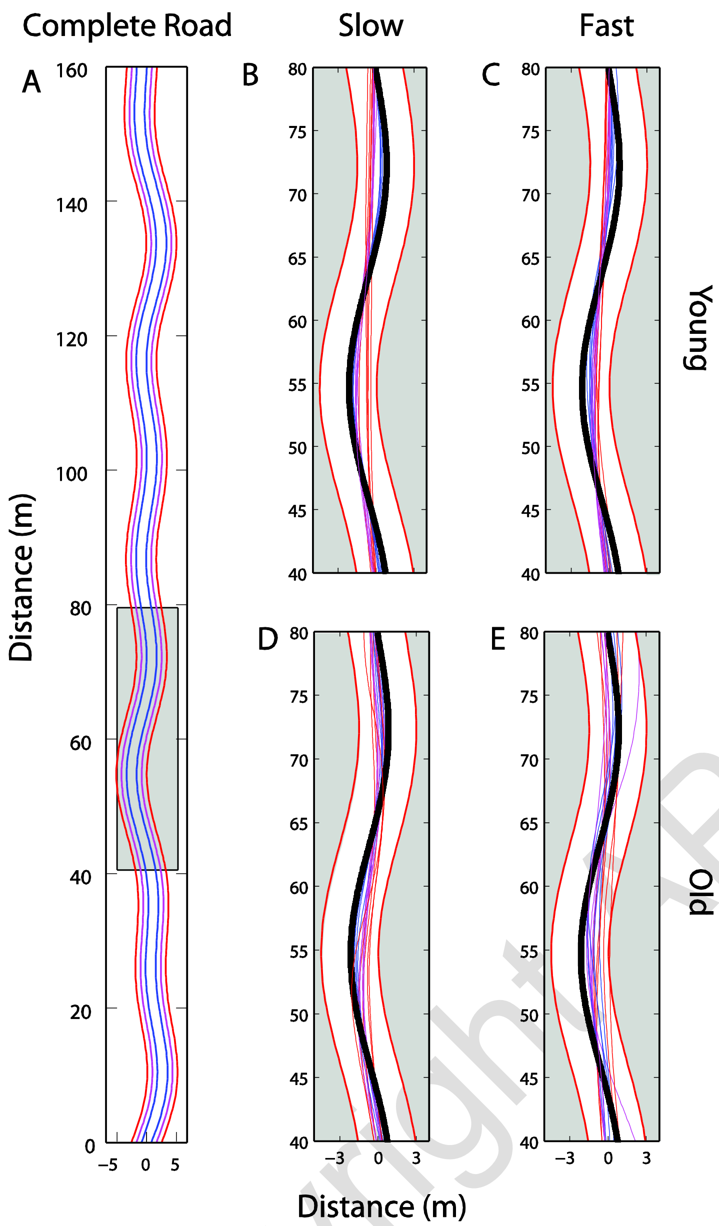

Figure 5. ***(a)*** *Sinusoidal roads of three possible widths: narrow (1.5 m, blue), medium (3 m, green) and wide (4.5 m, red). The grey box shows the section of road that is expanded in the remaining panels. For clarity only the widest (red) road edges are shown in panel's b-e.* ***(b)*** *Individual steering trajectories for a representative young participant on narrow (blue), medium (green) or wide (red) roads at slow speeds or* ***(c)*** *fast speeds. This young participant scored close to the mean group steering bias (mean steering bias = 0.47 m; group mean = 0.46 m).* ***(d)*** *Individual steering trajectories for a representative old participant on narrow, medium or wide roads at slow speeds or* ***(e)*** *fast speeds. This old participant scored close to the mean group steering bias (mean steering bias = 0.38 m; group mean = 0.40 m).*

General Discussion

These studies provide new insight into the effects of aging on motor control. Previous research has identified an age-related decline in movement speed, accuracy and consistency (e.g. Desrosiers et al., 1995; Verkerk, Schouten, & Oosterhuis, 1990 Morgan et al., 1994; Welsh, Higgins & Elliot, 2007). Our findings support past findings, but also indicate that older adults adopt a different movement strategy when faced with a motor task that requires them to move steadily under temporal and/or spatial task constraints. We demonstrated this first by analysing speed and accuracy in a manual motor task (i.e. tracing paths) and then analysing accuracy, precision and bias in a 'driving' scenario (i.e. steering along virtual roads). Using these tasks we established a tendency for older adults to remain closer to the middle of the path/road and slow their movements down when possible (relative to their younger counterparts) in order to avoid leaving the path. This suggests that older adults are sensitive to their level of motor skill and are capable of adjusting their movement strategy in order to meet task demands.

In our first experiment we measured movement time, error and path length in a task that required participants to trace paths of varied thickness at their own preferred speed, or under a temporal constraint (i.e. a controlled slow or fast pace). When speed was controlled there was little difference in MT between the path thickness conditions, but when participants traced at their preferred speed, thicker paths yielded shorter MTs. The fact that there was no interaction between age and path thickness suggests that the effect of path thickness on MT was not dependent on age. Hence the MTs of the old and young decreased by a similar amount as the path got thicker. On the other hand, the interaction between age and speed condition suggests that when tracing at their preferred speed, the older participants traced more slowly than the young. In other words, when placed under a temporal constraint the old and young traced at a similar speed, but when pacing themselves, the older participants preferred to reduce their speed. This is understandable since the older adults were worse at tracing the narrow path under constrained slow speeds, indicating deficits in visual-motor control. Using the error and path length measures, we were able to explore further the effects of path thickness and speed on corner-cutting behaviour. Corner-cutting increased as paths got thicker, which reflects the greater margin for error either side of the pen when tracing along a wider path. We also observed age differences in corner-cutting behaviour whereby older participants were less likely to cut-the-corner as path thickness increased (Figure 2b). It seems that the older participants were sensitive to their limitations and therefore preferred to slow down where possible and keep the pen closer to the middle of the path in order to compensate for motor variability.

In the second experiment we aimed to establish whether similar age differences could be identified within an alternative visual-motor scenario. Previous comparisons of hand-writing and walking movements demonstrate that general patterns of behaviour can be observed during both actions (Hicheur, Vielledent, Richardson, Flash & Berthoz, 2005). We used a comparable set of conditions to our tracing task in order to generate virtual roads of varied width, with slow or fast locomotor speeds. The patterns of behaviour did seem to generalise from tracing to steering, with similar effects of path width and locomotor speed on spatial strategy. Steering at faster speeds along wider paths yielded a greater degree of corner-cutting (as shown by steering bias and RMS error). We also observed age differences in steering, with older participants exhibiting more variable trajectories for all road widths and speeds. These findings may help to explain anecdotal reports that older drivers have a spatial bias towards the road centre. A middle-of-the-road strategy reduces the risk of crossing a road edge (just as keeping the nib of the pen close to the middle of the path can prevent error in tracing tasks). The compensatory steering strategy adopted by our older participants therefore seems appropriate given the greater variability observed in some conditions. This result also complements the findings of Trommershauser et al (2005), which suggests that the human nervous system is able to optimise actions by minimising the costs based on the variability present in the system.

Real-life Compensation

The finding that older people 'play it safe' compared to their younger counterparts is in line with research that suggests older drivers are more risk adverse in real-world situations. When comparing the nature of road accidents associated with old and young drivers, qualitative differences become apparent which imply heightened risk aversion within the older population (Anstey, Wood, Lord & Walker, 2005; McGwin & Brown, 1999). In McGwin and Brown's (1999) report, accidents involving young drivers were frequently a result of risk-taking behaviours such as drunk driving, whereas older drivers were more likely to be involved in accidents associated with fatigue, early/late night driving, travelling at high speeds or bad weather. Furthermore, older drivers were found to be over-represented in accidents characterised by difficulties with the perceptual-motor aspects of driving (e.g. failure to yield, heed stop signs/signals, attend to objects/people/vehicles, pull out at the correct time at intersections, turn or change lanes appropriately) suggesting that their greater incident rate is more to do with a decrease in skill as opposed to risk-taking behaviours and/or decisions. An older driver's reluctance to drive in these potentially hazardous situations could reflect an awareness of the threat that age-related motor decline poses to driver safety. Accordingly, the research implies that older drivers might implement a compensatory strategy of 'avoidance' whereby they steer clear of risky driving situations (e.g. rush hour, night-time driving), or a strategy of 'adjustment' whereby they modify their driving style to account for their difficulties (e.g. by reducing speed; Hakamies-Blomqvist, Mynttinen, Backman & Mikkonen, 1999; Horberry, Hartley, & Gobetti et al., 2004; Planek & Overend, 1973). Our findings reflect the latter method of compensation – a tendency to adjust steering movements in order to avoid error in light of heightened motor variability. Hence, older participants adjusted their position on the road to compensate for a decrease in their ability to maintain a consistent path. In real-life situations, older drivers also tend to compensate by slowing down (Garber & Gadirau, 1988). In our experiment, we kept speed constant (within trials) so that we could directly compare steering behaviour across age-groups, but it is likely that the spatial and temporal compensations interact within real world driving tasks. For instance, an older driver might slow down on a narrow road to decrease their path variability and/or allow them to avoid the need to cut corners. Nevertheless, our data show clearly that when these strategies are prevented because of external constraints (e.g. being in a stream of fast moving traffic) then the age-related deficits in skill become apparent. This finding has implications for the assessment of the older driver.

The costs of compensation

Compensatory strategies are not without cost. In the real world, a reduced consistency in road position makes it more difficult for the driver behind to safely complete manoeuvres that rely on the stability of the leading vehicle's road position (e.g. overtaking and merging). Likewise, driving too slowly increases the variance in the speed of vehicles travelling together which increases the risk of accidents (Garber & Gadirau 1988). Slow driving can frustrate other drivers leading to risky overtaking manoeuvres (McGwin & Brown 1999). It seems, therefore, that older drivers' compensatory strategies may not always be sufficient to ensure road safety. It is also important to note that our use of the word 'strategy' (both in reference to the first and second experiment) does not imply that the compensatory behaviour is a conscious decision. There may indeed be a tendency for older adults to consciously and strategically compensate for their difficulties. Nevertheless, more fundamental adaptations that are not cognitively penetrable might also result from the increased variability of signals within the aged nervous system (Desrosiers et al., 1995; Krampe, 2002; Smith et al., 1999; Verkerk, Schouten & Oosterhuis, 1990). The human nervous system appears to be sensitive to noise in the informational variables used to carry out skilled tasks such as reaching (Tresilian, Mon-Williams & Kelly, 1999), grasping (Ernst & Banks, 2002) and steering (Wilkie & Wann, 2002) with less reliable information being down-weighted. Thus, the bias towards adopting a particular spatial position might reflect low-level perceptual-motor adaptations to noise within the system. In older adults such noise is likely to be introduced both through degraded visual inputs as well as impaired motor outputs. In our experiments all participants reported normal (or corrected-to-normal) vision. However, without conducting extensive eye-examinations, we are unable to identify whether decrements in individual motor performance were caused primarily by visual impairments. The relatively homogenous behaviour of the older adults suggests that noise in the system was not solely due to visual problems. In fact, because the older adults experienced a greater degree of motion sickness in Experiment 2, it might be that they were particularly reliant on visual information. Following the curvature of the road requires larger changes in steering trajectory and results in a greater degree of rotation in the optic flow field. The steering strategy adopted by older adults (i.e. to follow the shape of the road) may therefore have led to elevated reports of motion sickness. Nevertheless, because a similar pattern of behaviour was observed in Experiment 1, where no motion sickness issues were reported, we do not feel that the age differences we report can be explained by this phenomenon.

Conclusions

The findings of the present experiments have two primary implications for future research. First, our use of a manual tracing task to measure spatial and temporal differences between old and young participants revealed a tendency for older people to slow their movements down and adjust their spatial strategy to avoid error (i.e. reduced corner-cutting on the wider paths relative to the young). The possibility that older adults are not only sensitive to their difficulties, but are also able to adjust their movement strategy accordingly poses implications for our approach to motor rehabilitation in the future. Essentially, it is important to establish how older people learn (whether consciously, or unconsciously) to adapt to their new diminished level of skill before prompting or teaching new methods in a rehabilitative setting. Second, the driving experiment revealed for the first time age differences in steering bias and variability, which may be informative in terms of maintaining road safety. Specifically, it is important to establish what strategies are adopted by older drivers in order to ensure their safety (together with the safety of other road users). The extent to which compensatory strategies preserve road safety is unclear, but the high crash rate for older drivers suggests that strategic compensations are not completely successful. Moreover, whilst there is evidence that compensatory strategies might help prevent accidents (De Raedt & Pondjaert-Kristoffersen, 2000) compensation is not always possible without incurring a cost. Hakamies-Blomqvist (1994) argued that avoiding potentially hazardous scenarios leaves a driver less able to cope when presented with an unavoidable situation. Likewise, compensating through speed reduction has a cost since it makes merging with motorway traffic difficult (de Waard, Dijksterhuis, & Brookhuis, 2009) and the further a vehicle's speed deviates from the average on a motorway, the greater the risk of accident

(Garber & Gadirau, 1988). In our study we found that the older group found it particularly difficult to steer down the narrow road at fast speeds and this was the only condition in which they exhibited similar amounts of corner-cutting to the young. Subsequently, it can be seen that the system will fail to compensate when put under pressure, placing the driver and other road users in danger.

References

Anstey, K. J., Wood, J., Lord, S., & Walker, J. G. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical Psychology Review, 25*, 45-65.

Billington, J., Field, D. T., Wilkie, R. M., & Wann, J. P. (2010). An fMRI Study of Parietal Cortex Involvement in the Visual Guidance of Locomotion. *Journal of Experimental Psychology: Human Perception and Performance, 36*(6), 1495-1507.

Clarke, D. D., Ward, P., Truman, W., & Bartle, C. (2009). *Collisions involving older drivers: An in-depth study*. London: Department for Transport.

Coutton-Jean, C., Mestre, D. R., Goulon, C., & Bootsma, R. J. (2009). The role of edge lines in curve driving. *Transportation Research Part F-Traffic Psychology and Behaviour, 12*(6), 483-493.

Culmer, P. R., Levesley, M. C., Mon-Williams, M., Williams, J. H. (2009). A new tool for assessing human movement: The Kinematic Assessment Tool. J*ournal of Neuroscience Methods, 184,* 184-192.

De Raedt, R. & Ponjaert-Kristoffersen, I. (2000). Can strategic and tactical compensation reduce crash risk in older drivers? *Age and Ageing, 29*, 517-521.

de Waard, D., Dijksterhuis, C., & Brookhuis, K. A. (2009). Merging into heavy motorway traffic by young and elderly drivers. *Accident Analysis & Prevention, 41*, 588-597.

Desrosiers, J., Hebert, R., Bravo, G., & Dutil, E. (1995). Upper-extremity motor coordination of healthy elderly people. *Age and Ageing 24*, 108-112.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*, 429-433.

Field, D. T., Wilkie, R. M., & Wann, J. P. (2007). Neural systems in the visual control of steering. *The Journal of Neuroscience, 27*(*30*), 8002-8010.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381-391.

Garber, N. J., & Gadirau, R. (1988). Speed variance and its influence on accidents. *AAA Foundation for Traffic Safety, Washington DC*.

Giampaoli, S., Ferrucci, L., Cecchi, F., Noce, C, L., Poce, A., Dima, F., Santaquilani, A., Vescio, M. F., & Menotti, F. (1999). Hand-grip strength predicts incident disability in non-disabled older men. *Age and Ageing, 24,* 283-288.

Hakamies-Blomqvist, L. (1994). Compensation in older drivers as reflected in their fatal accidents. *Accident Analysis & Prevention, 26,* 107-112.

Hakamies-Blomqvist, L., Mynttinen, S., Backman, M., & Mikkonen, V. (1999). Age-related differences in driving: Are older drivers more serial? *International Journal of Behavioral Development*, *23,* 575-589.

Hicheur, H., Vieilledent, S., Richardson, M. J. E., Flash, T., & Berthoz, A. (2005). Velocity and curvature in human locomotion along complex curved paths: a comparison with hand movements. *Experimental Brain Research, 162,* 145-154.

Horberry, T., Hartley, L., Gobetti, K., Walker, F., Johnson, B., Gersbach, S., & Ludlow, J. (2004). Speed choice by drivers: The issue of driving too slowly. *Ergonomics, 47*, 1561-1570.

Johnson, R.L., Culmer, P., Burke, M.R., Mon-Williams, M., Wilkie, R.M. (2010). Exploring structural learning in handwriting. *Experimental Brain Research, 207(3-4)*, 291-295.

Krampe, R. T. (2002). Aging, expertise and fine motor movement. *Neuroscience & Biobehavioral Reviews, 26*, 769-776.

Land, M., & Horwood, J. (1995). Which parts of the road guide steering? *Nature, 377(6547*), 339-340.

Mars, F. (2008). Driving around bends with manipulated eye-steering coordination. *Journal of Vision, 8,* 1-11.

Massie, D.L., Campbell, K.L., & Williams, A. F. (1995). Traffic accident involvement rates by driver age and gender. A*ccident Analysis & Prevention, 27,* 73-87.

McGwin, G., &Brown, D. B. (1999). Characteristics of traffic crashes among young, middle-aged, and older drivers. A*ccident Analysis & Prevention, 31*, 181-198.

Mioshi, E., Dawson, K., Mitchell, J., Arnold, R., & Hodges, J. R. (2006). The Addenbrooke's Cognitive Examination Revised (ACE-R): a brief cognitive test battery for dementia screening. Int*ernational Journal of Geriatric Psychiatry, 21,* 1078-1085.

Morgan, M., Phillips, J.G., Bradshaw, J.L., Mattingly, J.B., Iansek, R., & Bradshaw, J.A. (1994). Age-related motor slowness: simply strategic? *The Journals of Gerontology Series A: Biological and Medical Sciences , 49,* M133-M139.

Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences, 20*, 279-349.

Planek, T.W., & Overend, R.B. (1973). Profile of the aging driver. *Traffic Safety 13,* 9-13.

Rantenen, T., Guralnik, J.M., Foley, D., Masaki, K., Leveille, S., Curb, D.J., & White, L. (1999). Midlife hand grip strength as a predictor of old age disability. T*he Journal of The American meical Assosciation, 281,* 558-560.

Robertshaw, K.D., & Wilkie, R.M. (2008). Does gaze influence steering around a bend? *Journal of Vision, 8* (4-18), 1-13.

Salvucci, D. D., & Gray, R. (2004). A two-point visual control model of steering. *Perception, 33(10*), 1233-1248.

Schmidt, R.A., & Lee, T.D, (1999). *Motor Control and Learning. A Behavioral Emphasis.* Europe: Human Kinetics.

Smith C.D., Umberger, G.H., Manning, E.L., Slevin, J.T,. Wekstein, D.R., Schmitt, F.A., Markesbery, W.R., Zhang, Z., Gerhardt, G.A., Kryscio, R.J., & Gash, D.M. (1999). Critical decline in fine motor hand movements in human aging. *Neurology, 53,* 1458-1461.

Tresilian, J.R., Mon-Williams, M., & Kelly, B.M. (1999). Increasing confidence in vergence as a cue to distance. *Proceedings of The Royal Society Series B: Biological Sciences, 266*, 39-44.

Trommershauser, J., Gepshtein, S., Maloney, L.T., Landy, M.S., & Banks, M.S. (2005). Optimal compensation for changes in task-relevant movement variability. *Journal of Neuroscience, 25,* 7169-7178.

Verkerk, P.H., Schouten, J.P., &Oosterhuis, H. (1990). Measurement of the hand coordination. *Clinical Neurology and Neurosurgery,* 92, 105-109.

Welsh, T.N., Higgins, L., & Elliot. D. (2007). Are there age-related differences in learning to optimize speed, accuracy and energy expenditure? *Human Movement Science, 26,* 892-912.

Wilkie, R. M., Kountouriotis, G. K., Merat, N., & Wann, J. P. (2010). Using vision to control locomotion: looking where you want to go. *Experimental Brain Research, 204(4)*, 539-547.

Wilkie, R.M., & Wann, J.P. (2002). Driving as night falls: The contribution of retinal flow and visual direction to the control of steering. *Current Biology, 12,* 2014-2017.

Wilkie, R. M., & Wann, J. P. (2003). Controlling steering and judging heading: Retinal flow, visual direction, and extraretinal information. *Journal of Experimental Psychology: Human Perception and Performance, 29(2),* 363-378.