Inter and intra-individual differences in steering wheel hand positions during a simulated driving task

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This paper describes an experimental study focusing onto the way drivers use the steering wheel while performing a 2D tracking task. The stimulus during this task was a steering wheel angle signal recorded in real situations involving turns and straight lines performed at about 30 km/h. The hand positions of 20 volunteers were recorded in 6 steering scenarios involving 7 road geometries using a 3D motion capture system. The hand movement data were analysed via a descriptive/inferential procedure: each hand was considered using nine indicators – eight membership value averages linked to eight fuzzy angle windows and a frequency value related to the off steering wheel position – while the indicators were investigated using multiple correspondence analysis and non-parametric global and post-hoc tests. Results showed that inter-individual differences were larger than intra-individual differences. Considering 2 £ 9 = 18 windows, the inter-individual differences mainly appeared during two main kinds of steering hand strategies: with versus without crossing hands, the latter being the most often used (17 among 20 participants). The intra-individual data showed that some drivers maintained a nearly identical strategy for all road geometries, while other drivers changed their hand position with the direction and/or maximum angle value of the turn.

Practitioner Summary: Understanding hand position strategy could be used to design steering wheel assistance in relation to a driver’s physical resources with a view to adapting the steering wheel to disabled drivers.

Keywords: motion analysis; driving; steering wheel; hand-positioning strategies; driving simulator

1. Introduction

Steering wheel angle is one of the most often used signals in driving studies either in real environments (Isomura, Hara, and Kamiya 1995; Dubart 2009; Collet, Guillot, and Petit 2010; Valero-Mora et al. 2013) or simulated situations (Rannay, Simmons, and Masalonis 1999; Van Winsum, De Waard, and Brookhuis 1999; Salvucci and Liu 2002; Hancock and De Ridder 2003; Younssi et al. 2011; Gabrielli et al. 2012; Saffarian, Happee, and de Winter 2012; Deroo, Hoc, and Mars 2013; Van der Zwaag et al. 2013; Ross et al. 2014). The main reasons are that this signal is easy to record and to summarise via indicators, giving useful information about the driver/car/environment system state, e.g. the arithmetic mean or the standard deviation (Rannay, Simmons, and Masalonis 1999; Van Winsum, De Waard, and Brookhuis 1999; Lenneman and Backs 2009; Valero-Mora et al. 2013; Ou, Liu, and Shih 2013).

On the opposite, studying hand position in relation to the steering wheel is less often encountered, even though such position is essential to control the car trajectory. One reason is the difficulty to obtain real-time measurements. For instance, in simulated situations, a biometrical approach via a 3D imaging system (at 50 Hz or even more) may be used (Carey et al. 2008; Kyung, Nussbaum, and Babski-Reeves 2010). Using dynamometric sensors allows to obtain some information about the hand positions and efforts in relation to the steering wheel (Gabrielli et al. 2012). The second difficulty is to compute simple statistical indicators (as those computed from the steering wheel angle signal) due to the presence, for each hand, of a complex scale containing both a qualitative aspect (the hand is either on or off the steering wheel) and a quantitative aspect (the angle value in the on case). Furthermore, as stated by Burgess-Limerick, Zupanc, and Wallis (2012), computing averages of angle values with the interval [0, 2π] or [−π, π] may have a poor meaning (see Section 2.3 for some examples).

Instead of automatic measurement devices, the position variables may be obtained via naturalistic observation in either actual situations (Walton and Thomas 2005; Thomas and Walton 2007; Fourie, Walton, and Thomas 2011; Jonsson 2011) or in simulated situations (De Waard, Van Den Bold, and Lewis-Evans 2010). In studies based on field observations, some authors suggested that the hand position on the steering wheel could reflect the perceived road environment risk, the later...
being taken into consideration using the number of hands – 0, 1 or 2 – present in the 9 and 3 o’clock positions (Walton and Thomas 2005; Thomas and Walton 2007). In a more recent study, still with a real situation (Jonsson 2011), photographs were taken from a bridge and then changed into qualitative data using two level sets: a set containing the 9, 10, 11, 12, 1, 2 and 3 o’clock dial positions (thus seven levels) and a set containing the below position coded as 0 (thus one level, the camera angle was such that it was not possible to determine more accurately the hand position; the 0 position also included driver hand positions in non-contact to the steering wheel). In these original studies, only a part of the steering could be viewed. Another study was conducted in a driving simulator while merging into motorway traffic (De Waard, Van Den Bold, and Lewis-Evans 2010). The hand position was classified into three categories: high, medium and low control. For instance, if the right and left hands were observed at 2 or 3 o’clock and 9 or 10 o’clock, respectively, this hand position combination was categorised as high control in a road environment risk.

In this study, the hand position is analysed using a driving simulator and a 3D imaging system to understand How are inter- and intra-individual differences in hand positions during the steering wheel task with ‘standard’ drivers? This question is the first stage of the VolHand project, the main objective being to create a new control law of electric power assisted steering system for drivers with upper-limb disabilities. If the first stage focuses on ‘standard’ drivers, the need to use the simulator with both kinds of drivers resulted into designing and building an experimental device that can be easily moved from our laboratory to hospitals (this second kind of location is due to the requirement of the attendance of doctors). The first stage of the study is presented using three main sections. Section 2 presents the experiment and the statistical approach enabling intra- and inter-individual differences to be shown. Section 3 presents the statistical analysis results and Section 4 discusses the analysis output. Given the easy-to-move constraint of our 3D measurement-based simulator, the driving situations tested here are far from those of either fixed or dynamic simulators (Beh and Hirst 1999; Reed and Green 1999; Younsi et al. 2011; De Winter et al. 2009; Wang et al. 2010; Saffarian, Happee, and de Winter 2012) and even more far away from on-road situations (Walton and Thomas 2005). Thus ecological validity is also discussed below.

2. Methods
2.1 Experimental system
The experimental system consisted of a driving simulator associated with a VICON motion capture system and a digital camera (Schiro 2013).

The driving simulator was built using a wrecked car purchased from a scrap yard. The car was cut to facilitate motion capture and the engine compartment was maintained to offer sufficient space for instrumentation. The dashboard, seats and central console (i.e. the handbrake and gear shift) were kept to maximise the driver’s immersion. Seats remained fully adjustable to guarantee optimal driver-steering wheel positioning. Finally, a video projector was inserted into this framework through the car’s brand logo and a screen displayed the video to the driver. A steering input device (SID) from a steer-by-wire system was mounted in place of the original drive shaft and wheel. The SID was provided by a steering system major company (e.g. JTEKT corporation, also deeply involved is this study). The SID system was powered by a battery and connected to an electronic control unit in a Controller Area Network bus with a dSpace MicroAutobox to ensure a real-time connection with the computer running the simulation software. The MicroAutobox was loaded with a Matlab/Simulink model to enable the reaction torque applied to the drive shaft to be computed in real time and to remain consistent with the simulated speed and the steering wheel angle (Gabrielli et al. 2012).

Hand kinematics was obtained through a VICON MX T020 motion capture system. Ten infrared cameras surrounded the test rig to maximise visibility of the upper limbs and trunk. Marker positions were recorded at a 100 Hz sampling frequency. Reflective markers were placed on the driver’s second and fifth metacarpals on the right and left hands using a double-sided rubber band. These markers’ gravity centre was used to characterise the hand angle position in relation to the steering wheel, with 0° corresponding to a top hand position, a positive angle (from 0° to 180°) to a hand situated on the right side and a negative angle (from 0° to −180°) to a hand situated on the left side.

A 1.6-megapixel digital video camera was used for additional validation. The video camera was placed behind the driving simulator to capture the driver’s upper limbs throughout the experiments. Marker positions were filtered and resampled at 25 Hz. Additional post-processing was achieved to build hand angle position sets with minimal corrupted data (as shown in the next section, the data analysis stages will be performed so that all individual data sets are visualised, thereby improving confidence in the database). This processing stage was performed using Matlab.

2.2 Experimental protocol and participants
The steering exercise involved following a line scrolling downwards on the screen and lasted 2 min. The line reproduced the steering wheel angle signal that had been recorded on a car on the Valenciennes University campus (the experimenter was
driving at about 30 km/h). Completing the exercise required the participant to steer the wheel to maintain a coloured dot on the line. The driver received feedback: the dot remained green when it stayed on the line and turned red whenever it deviated from the line (Schiro et al. 2011). After several trials, the tolerance was set to ± 25°. Each steering scenario fell into seven road geometries and eight short straight lines. The road geometries were steering angle from traffic circle and sharp or moderate bend. A steering scenario example is shown in Figure 1 (further information about the real road geometries and stimuli histograms can be found in Figure A of the Electronic Appendix).

Training sessions were performed prior to the real steering exercises to enable the driver to get accustomed to the task and therefore feel comfortable. Then, the driver performed six steering scenarios: the seven road geometries were randomly distributed for each scenario. Drivers had a 30-s break between each steering scenario. Tracking quality was estimated as the ratio between the time during which the dot remained green and overall scenario time. A ratio, referred to as a ‘score’, of above 90% was considered acceptable and enabled the data thus acquired to be used (Schiro et al. 2011).

The driver sample included 20 volunteer subjects, 8 women 12 men, each with a valid driving licence and without any upper limb disability (mean age = 31 years; SD = 11; in fact the initial number of participants was 33, but for reasons of too frequent loss of markers, only 20 individuals are hereby considered). All drivers obtained a score above 90% during the steering task tests.

2.3 Statistical analysis

First, the experimental database can be seen as a combination of $I \times J \times K = 20 \times 7 \times 6 = 840$ situations, whereas $I$, $J$ and $K$ represent the number of individuals, road geometries and repetitions, respectively, and each situation yields bivariate signals (one time variable for each hand). With such a large and complex database, checking data and showing driver, road geometry and repetition effects are first required. Both tasks can be performed using descriptive statistics. Magnitude histogram and factor analysis tools are privileged because the first tool keeps all the data pieces (for each hand, the histogram is built from all database time samples), while the second tool maintains both multivariate and multifactor aspects with a low data reduction level, stated as follows.

Comparisons between individuals, road geometries and repetitions require time averaging, and the usual indicators, such as arithmetic means and SDs, may lead to significant information loss. For instance, if two angle positions for one hand

Figure 1. Illustration of the simulator-based study. (a) Overview of the experimental platform. (b) Example of a steering scenario composed of seven road geometries (the sequence of the seven road geometries is different in the five other scenarios).
are $\alpha_1 = -90^\circ$ (9 o’clock position on the left side of the steering wheel) and $\alpha_2 = 90^\circ$ (3 o’clock position on the right side of the steering wheel), the time average is $\alpha = 0^\circ$ (top position), which is far from both initial positions. To palliate this problem, the complete 360$^\circ$ range was divided into $S = 8$ fuzzy blocks (see Figure 2(a) and the Part B Electronic Appendix for further details). Membership functions (Karwowski 1991) are labelled so that the statistical analysis outputs can be deciphered easily and quickly. Therefore, instead of considering numbers ranging from 1 to 8, one letter label is used for each hand with (1) $L$, $R$, $B$ and $T$ for Left, Right, Bottom and Top modalities and (2) the following mnemonic technique is used for the four other positions: for the two other low positions, we consider pedal positions with letter $A$ for the Accelerator pedal and letter $K$ for the braKe pedal; for the two high positions, we suggest keeping in mind the relative positions of the two mirrors (for a right-handed driver), i.e. $X$ for eXterior mirror and letter $N$ for iNterior mirror. To distinguish between right and left hands, capital and small letters are used. Figure 2(a),(b) shows the space windowing notation. With this principle, each time sample at 25 Hz yields eight membership values for each hand (see Figure 2(d) for a numerical example).

A final argument in favour of space windowing is worth noting: it makes it possible to consider both quantitative and qualitative aspects for the hand position variable. In addition to the quantitative hand position (ranging from $-180$ to $+180^\circ$), an ‘Off steering wheel’ verbal nuance must be considered (Figure 2(c)): the membership value is set as 1 as soon as the hand leaves the steering wheel, i.e. the hand’s gravity centre is located at a position greater than that of the mean hand position + 3.5 cm lengthwise and the wheel radius ± 6 cm widthwise. Thus $8 + 1 = 9$ membership values are present for each measurement variable (here each hand), and a grand total of $2 \times 9 = 18$ space windows (SWs) exist for both hands. When the right hand does not stay on the steering wheel, the letter $O$ is used for Off ($o$ for the left hand).

Finally, for each of the $20 \times 7 \times 6 = 840$ bivariate signals, membership value averages (MVAs) are computed from the corresponding time samples (Loslever and Ranaivosoa 1993; Loslever 1993). Thus the characterisation stage yields a large table with 840 rows and $2 \times 9 = 18$ columns and several other tables may be considered depending on the way MVAs are summarised, i.e. across one or two factors, see Figure B top part of the Electronic Appendix. To analyse these tables first using a descriptive approach, multiple correspondence analysis (MCA) (Benzecri 1992) was used. A useful summary is presented in Miyake, Loslever, and Hancock (2001) with tracking data (with more or less the same windowing principle for

![Figure 2](image-url)

**Figure 2.** Space windowing principle. (a) Definition of the eight SWs and related labels when the hand lays on the steering wheel for a given hand (e.g. when *The right hand is situated on top of the steering wheel, at about 0°*, the SW label is $T$, and $t$ for the left hand). An example showing two hand positions is also presented with left and right hands being indicated using red and blue, respectively. (b) Fuzzy membership function design for each hand. (c) Need to consider a new modality when the hand does not remain on the steering wheel. (d) Example of $2 \times 9 = 18$ membership values to the 18 SWs.
the angle scale) and a second example can be found in Loslever and Ranaivosoa (1993) with epidemiological and biomechanical data. To summarise, MCA is based on the same principle as the usual principal component analysis (PCA), except that MCA is used for frequencies (or membership values with fuzzy windowing). As with PCA, the column points may have more or less large relative contribution to the principal axis control. For instance, let us consider both cases: (1) a column \( c \) presents 840 random MVAs and (2) two columns \( c' \) and \( c'' \) are rather well connected, i.e. for 200 experimental situations, both the \( c' \) and \( c'' \) MVAs are high, while the contrary stands for the other 640 situations. In both cases, \( c' \) and \( c'' \) relative contributions are much higher than \( c \) contribution to control a principal axis. Furthermore, this axis will oppose the 200 experimental situations to the others. Further information about MCA output and the effect size is presented in the text and in Figure B of the Electronic Appendix.

With the same input (an MVA table), it is worthwhile comparing MCA with a more often used descriptive multidimensional method, i.e. hierarchical clustering (HC) (Jobson 1992; Kyung, Nussbaum, and Babski-Reeves 2010; Choi et al. 2012), see the final section of the Electronic Appendix. With the MVA table, the chi-squared distance (as with MCA) is chosen and the Ward agglomerative index, one of the most frequently used indices, is selected (Kyung, Nussbaum, and Babski-Reeves 2010).

Once the main trends have been displayed using a descriptive context with 18 MVA indicators, data may be studied via an inferential context. The inference analysis is not multivariate insofar as only indicators playing a major part in MCA are considered, and one by one. It is worthwhile reiterating that the membership value sum computed for the 9 windows is 1; therefore, it is possible to have linked indicators. That is why the indicator with the highest contribution to control a given axis is considered (the link absence will be checked anyway). In addition to that, since most MVA data are well outside the Laplace–Gauss distribution, the use of a non-parametric approach is better. Due to the presence of dependent samples with a road geometry factor exceeding two levels, a non-parametric analysis of variance procedure is used, i.e. Friedman two-way analysis of variance by ranks (FAVRs; Sheskin 2007). This global test is followed by pairwise comparisons (Sheskin 2007). All the tests are performed using 0.05 as the critical value. Both descriptive and inferential context analyses are performed using the statistical package \( R \).

3. Results

3.1 Descriptive analysis

Left and right angle distributions computed from the entire database were consistent with the task: (1) most values for the left hand were on the left side (between \(-180^\circ\) and \(0^\circ\)) with a dissymmetrical pattern and one mode at about \(-50^\circ\) and (2) the right hand distribution was quite symmetrical compared with the opposite hand, with \(0^\circ\) as symmetry axis, see Figure C of the Electronic Appendix. The root mean square error between the target steering wheel angle and the measured steering wheel angle was about 17°. There were 10% (respectively, 9%) of observations corresponding to the SW ‘the left (respectively, right) hand is off the steering wheel’. Given in Figure 2, the 18 MVA series computed from the entire database also showed a fairly symmetric aspect with respect to the vertical axis, see Figure 3 top left. This plot also displays a dissymmetrical aspect with respect to the horizontal axis: the steering wheel top was more often used than its bottom part. The 18 MVA series for each of the seven road geometries reveal that road geometry did not have much influence (Figure 3).

To appraise more directly both intra- and inter-individual differences and SW accounting for those differences, MCA with a table including \( I \times J \times K = 20 \times 7 \times 6 = 840 \) observations and \( 2 \times 9 = 18 \) SW is performed. It is worth noting that measurements are not independent (i.e. the true sample size is 20 and not 840), but, for a preliminary descriptive analysis, giving the same status to each of the three factors is preferable (840 rows being a large number for the row points, 20 individuals subplots will be displayed instead of a single plot). The first two main axes featuring much higher relative inertia than the next ones (21% and 18% versus 13% and 8%), only two dimensions are considered here. With these first two main axes, the main MCA results are as follows:

1. Among the set of \( 2 \times 9 \) SW points, the subset that enabled the driving behaviour to be distinguished mainly contained \( A, R, k \) and \( o \), Figure 4. Consequently, Axis 1 opposes two kinds of behaviour:

   Type 1 behaviour. On the positive side, there are empirical situations where the behaviour is as follows:

   - SW \( o \) is highly present, i.e. the left hand is rather frequently positioned off the steering wheel (compared with the average profile computed from all 840 situations; remember that this average profile is located where the main axes intersect) and

   - SWs \( A, R \) and \( k \) are less present, i.e. the right hand is rarely on the bottom-right part of the steering wheel (neither about 90° nor 135°) and the left hand is rarely about the \(-135^\circ\) position,

   Type 1’ behaviour. On Axis 1 negative side, there are empirical situations with an opposite behaviour.

2. On Axis 2, which is mainly controlled by windows \( n, r \) and \( X \), outlines an opposition as follows:
Type 2 behaviour. On the positive side, there are empirical situations where
- SWs \( n \) and \( r \) are highly present, i.e. the left hand often moves onto the top right part of the steering wheel (about \( 45^\circ \) or \( 90^\circ \)) and
- SW \( X \) is less present, i.e. the right hand is rarely about the \(-45^\circ\) position,

Type 2’ behaviour. On Axis 2 negative side, there are empirical situations with an opposite behaviour. From the respective positions of \( I \times J \times K = 20 \times 7 \times 6 = 840 \) observation points, the effect of the repetition factor is much lower than with the individual and road geometry factors (see Figure D of the Electronic Appendix with a different colour for each road geometry). For a better understanding into the influences of these two latter factors, MVA may be averaged across repetitions and the \( I \times J = 140 \) points considered as supplementary row points (see table \( Y_{IJ} \) in Figure B of the Electronic Appendix). MCA output yields Figure 5 from which the main results are as follows:

![Figure 3. Height sets of 18 MVA (the two bar graphs located outside the circle show MVA for cases where a hand does not remain on the steering wheel; the left and right hands are indicated using red and blue, respectively, and lower and upper cases, respectively, see Figure 2 for the space windowing model). The top-left subplot shows the 18 MVA for the ‘average’ of the 7 road geometries and the 7 other subplots show the 18 MVA for 7 road geometries (avg means average).](Image)
Drivers present intra-individual differences of varying degrees. For the low variation case, e.g. drivers Ib, Mu and Ys, the seven road geometries yield quite similar MVA sets. For the high variation case, there are drivers with large intra-individual differences along one axis (e.g. Ac) and along both axes (e.g. Hm).

* Drivers presenting point clouds have different positions along both axes, e.g. Ts is on the far right side of Axis 1 (see Type 1 behaviour mentioned above) and Ys is on the far left side of Axis 1.

In order to assess both intra- and inter-individual differences more directly, average profiles can be computed for the $I = 20$ individuals, $J = 7$ road geometries and the $K = 6$ repetitions, each of the $20 \times 7 + 6$ MVA profile being considered as supplementary row points (see table $Y_I$, $Y_J$ and $Y_K$ in Figure B of the Electronic Appendix). Figure 6 clearly shows the hierarchy of factor effects, the individual factor having the higher effect and the repetition factor the lower effect. Effect sizes computed from MCA point positions in the main plane are 0.36, 0.28 and 0.04, respectively (see the Electronic Appendix for the computational method). Effect sizes computed from MVA profiles in a $2 \times 9 = 18$ dimensional space are 0.26, 0.15 and 0.05, respectively (see the Electronic Appendix for the computational method); these three values are MCA output consistent. Given the intra- and inter-individual differences underscored by MCA plots, MVA profiles and signals are now considered.

### 3.1.1 Difference between individuals

Let us focus on two individuals who appeared as opposites according to Axis 1, such as Ys on the far left and Ts on the far right, shown in Figure 6(a). Considering both Figures 4 and 6(a), driver Ts is on the far right of Axis 1 due to a type 1 behaviour. Indeed, driver Ts keeps his hands off the steering wheel more often than driver Ys. The two sets of 18 MVAs in Figure 7 show such a behaviour: $o$ and $O$ frequencies are higher for driver Ts. To explain this behaviour more accurately, it
Figure 5. MCA output from a table crossing $20 \times 7 \times 6 = 840$ observations and $2 \times 9 = 18$ SWs. Case of the first main plane with $20 \times 7$ average profiles projected as supplementary row points (the 20 individual subplots are shown separately, each subplot displaying 7 road geometry points).
is necessary to return to the initial data (see the cell shown in Figure B left top of the Electronic Appendix). Figure 8 shows the same road geometry and the same repetition for drivers Ys and Ts. First, let us compare, for driver Ys, the two magnitude histograms for each hand, Figure 8(c),(e), with Figure 7(a). Keeping in mind that the seven road geometry points on MCA output are rather close to one another for driver Ys (see Figure 5), Figure 7(a) is consistent with Figure 8(c),(e). For instance, for the left hand, Figure 7(a) shows that most angle values are encapsulated within SWs x, l and k, and that the most frequently used window is l. This result is consistent with Figure 8(c), which shows that most angle data range from $-45^\circ$ to $-135^\circ$. As regards the histogram, pattern for the right hand, Figure 8(e), is slightly different: although most angle values range from $45^\circ$ to $135^\circ$ (thus a symmetrical angle domain compared with the opposite hand), there is a small modal area at approximately $-135^\circ$. To explain these two histograms, let us now focus on the time excursion (from both signals shown in Figure 8(a), but from a careful video analysis also). At the beginning of the signal, there is a short straight road (see the [0s, 2s] time window of Figure 8(a)) and the left-hand angle position remains at about $-90^\circ$, then comes a left turn and a right turn, during which the hand remains close to $-90^\circ$. Indeed driver Ys keeps the left and right hand on the left and right side of the steering wheel, respectively. The bottom of the steering wheel is used more frequently than the top of the steering wheel: to turn to the left, the left hand turns the wheel to about $-135^\circ$ and is replaced by the right hand to continue turning the wheel. The left hand goes back to about $-90^\circ$ to turn the wheel again. The hands never cross. This hand strategy is favoured by Ys for all road geometries. Left and right angle signal excursions are consistent with the type 1’ behaviour.

Figure 6. MCA output from a table crossing $20 \times 7 \times 6 = 840$ observations and $2 \times 9 = 18$ SWs. Case of the first main plane and average profiles displayed as supplementary points (the points do not participate in a main axis control): (a) 20 individuals, (b) 7 road geometries and (c) 6 repetitions.

Figure 7. MVA sets for two individuals appearing different according to MCA Axis 1 (see Figures 4 and 5). The two bar graphs located outside the circle show MVA for cases where a hand does not remain on the steering wheel; the left and right hands are indicated using red and blue, respectively, and lower and upper cases, respectively, see Figure 2 for the space windowing model.
stated above. Thus one possible denomination of type 1’ behaviour could be ‘without hand crossing behaviour’ (commonly called hand-to-hand steering or push/pull steering). Moreover, Figure 5 for driver Ys shows that the seven road geometry points are close, revealing highly repetitive behaviours.

Let us now focus on driver Ts (Figure 8, left side). For the left hand, the Ts histogram modal area is less towards the negative values than the Ys histogram modal area. Moreover, for both hands, the frequencies of the ‘off steering wheel position’ (FO indicators) are much higher for driver Ts and for driver Ys, the difference being much higher for the left hand.

Figure 8. Signals and magnitude histograms for two individuals appearing different according to MCA Axis 1 (see Figures 4 and 5). (a) and (b) Each plot displays three signals: the steering wheel angle, in black, and the hand angular positions in relation to the steering wheel, in red and blue for left and right hands, respectively, with signal blanks corresponding to cases where the hand does not stay on the steering wheel (the frequency of such cases is indicated using the FO indicator); the main difference is that driver Ys does not cross hands while the contrary stands for driver Ts. (c)–(f) Each plot displays the histogram of the hand angular position signal. 
Such differences can be explained using time excursion. Driver Ts crossed hands to steer the wheel because he used the upper part of the wheel: for instance, during a left turn situation (Figure 8(b) from \( t = 0 \) to \( 4s \)), the left hand releases the wheel at \( t = 2s \) and the right hand continues to steer the wheel until \( -135^\circ \), while the left hand reaches the left top portion of the steering wheel (around \( -45^\circ \)). Left and right angle signal excursions are consistent with the type 1 behaviour stated above (Axis 1 positive side). Thus one possible designation could be ‘with hand crossing’ (commonly called hand-over-hand steering).

### 3.1.2 Difference between road geometries

Let us now focus on the differences underscored by Axis 2. In Figure 5, individuals for which the seven road geometry points are quite different often have points 2 and 5 at the top of Axis 2, while the contrary is true for points 4 and 6. Thus, Axis 2 seemingly shows the road geometry influence. To assess intra-individual differences, let us focus on driver Ec, featuring rather large differences in road geometries 2 and 6. Keeping in mind that Axis 2 was mainly built from modalities \( n \) and \( r \) (on the positive side, see Figure 4) and \( X \) (on the negative side), the MVAs for these three modalities (see Figure 9) are consistent with the relative positions of Figure 5. For instance, if one focuses on \( n \) and \( r \) modalities, Figures 4 and 5 show that driver Ec should have higher MVA for road geometry 2 than for geometry 6. This is confirmed in Figure 9. Figure 10 shows that driver Ec crosses hands on both road geometries.

### 3.1.3 Difference between repetitions

MCA of a table containing all the MVAs (see table \( Y_{ijk} \) in Figure B of the Electronic Appendix) shows a low effect over the repetition factor, MCA may be tried with MVA being averaged across repetitions (table \( Y_{ij} \)). SW positions and contributions are quite identical with those of the initial MCA (see Figure E of the Electronic Appendix). The relative positions of the \( 7 \times 20 \) points, 20 individuals, 7 road geometries and 6 repetitions are quasi identical to those of Figures 5 and 6, which confirms that the repetition factor effect size is quite low.

Figure 11, showing the HC output for the 18 SWs, is quite consistent with Figure 4, e.g. both figures show that \( x \) and \( N \) points are close (for these two windows, the MVA profiles are quite identical, each profile containing \( 20 \times 7 \times 6 = 840 \) values) and \( B \) and \( K \) points are quite distant. Clustering of the \( 20 \times 7 \times 6 = 840 \) observations shows that the first steps of the agglomerative algorithm merge, in most cases, repetition points of a (individual, road geometry) given pair, which means that the repetition factor effect is lower than the individual or road geometry effects (the dendrogram is not shown due its huge size). Here again the HC result is MCA consistent.

Given the main trends outlined by the descriptive multivariate analysis, let us continue using an inference monovariate analysis.

![Figure 9](image_url)

**Figure 9.** MVA sets for an individual who yields different road geometry points according to MCA Axis 2 (see Figures 4 and 5). The two bar graphs located outside the circle show MVA for cases where a hand does not remain on the steering wheel; the left and right hands are indicated using red and blue, respectively, and lower and upper cases, respectively, see Figure 2 for the space windowing model.
3.2 Inferential analysis

Since the repetition factor has a low impact (compared with the individual and road geometry factors, see Figure 6), MVAs are averaged across the six repetitions (allowing to improve statistical reliability of the results). With the two remaining factors, the FAVRs is used to assess the road geometry factor effect. Given the presence of seven levels for this factor, FAVR test is followed by pairwise comparisons, thus with $7(7 - 1)/2 = 21$ difference scores between rank sum pairs.

As stated in the Method section, these tests focus on indicators playing a main role in building the two MCA main axes.

Figure 10. Signals and magnitude histograms for an individual yielding different geometry points according to MCA Axis 2. (a) and (b) Each plot displays three signals: the steering wheel angle, in black, and the hand angular positions in relation to the steering wheel, in red and blue for left and right hand, respectively, with signal blanks corresponding to cases where the hand does not stay on the steering wheel (the frequency of such cases is indicated using the $FO$ indicator). (c)–(f) Each plot displays the histogram of the hand angular position signal.

3.2 Inferential analysis

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As stated in the Method section, these tests focus on indicators playing a main role in building the two MCA main axes,
Figure 4, i.e. on indicators linked to SW $o$ (The left hand is off the steering wheel, see Axis 1 positive side) and to SW $n$ (The left hand is at about 45°, see Axis 2 positive side; as shown by MCA, both indicators are independent, e.g. the linear correlation coefficient is close to zero: $-0.04$).

Tests concerning The left hand is off the steering wheel MVA ($o$). FAVR test results show that this indicator is significantly affected by the road geometry level. Moreover, there are 8 paired comparison tests of the 21 tests that yield significant differences (Figure 12(a)). The MVA values are consistent with MCA output: for instance, according to Axis 1 (Figure 4), road geometries 5 and 6 should have high values (compared with the average, see Axis 1 positive side of Figure 6(b)), while the reverse should be true for road geometries 2 and 7. Figure 12(a) is consistent with MCA output.

Tests concerning The left hand is at about 45° MVA ($n$). Likewise, the road geometry factor has a significant effect, but the number of significant comparison tests is slightly higher than previously, i.e. 11 tests versus 8 tests, see Figure 11(b). This result is MCA consistent: the road geometry factor effect size is higher with Axis 2 than with Axis 1, see Figure 6(b).

4. Discussion and conclusion

It is our hope that, using non-standard statistical tools and methods of ergonomics, we have opened an original window onto the signal behaviour analysis by examining how (fuzzy) parts of time variable scales are used by participants. First, the data analysis started using, for each hand-related position variable, a nine-window scale segmentation – through eight fuzzy membership functions when the hand is on the steering wheel and one crisp function otherwise. Then it was possible to get, for each (participant, road geometry, repetition) triplet, an accurate characteristic of the signal behaviour (e.g. more accurate than the usual arithmetic mean); see (Loslever, Popieul, and Simon 2003) for more details about data characterisation method comparison. Then, by using MCA with a grand table crossing $20 \times 7 \times 6 = 840$ observations (20 participants, 7 road geometries and 6 repetitions) and $2 \times 9 = 18$ SWs (9 SWs per hand, see Figure 2), (2) the distance between two SW points is the Chi-square measurement (as with MCA) and the agglomerative index is that of Ward.

Figure 4, i.e. on indicators linked to SW $o$ (The left hand is off the steering wheel, see Axis 1 positive side) and to SW $n$ (The left hand is at about 45°, see Axis 2 positive side; as shown by MCA, both indicators are independent, e.g. the linear correlation coefficient is close to zero: $-0.04$).
(e.g. $A$, $R$ and $k$ are often present compared with the average profile, while the contrary stands for $o$) versus ‘crossing’. This distinction may be seen as trivial but, retrospectively, the pair (space windowing, MCA) has been a poor couple of methods had this type of result not appeared first.

In terms of the inter- and intra-individual differences results, we have found a hierarchy of global factor effects as follows: (1) individual, (2) road geometry and (3) repetition (Figure 6); thus, generally speaking, inter-individual differences were greater than intra-individual differences. This main trend is consistent with what Bellet dubbed the ‘driving pattern’ (Bellet 1998). The drivers create their own way of turning the steering wheel based on whatever information gleaned when they learnt to drive. According to Michon (1985), driving strategies used by the driver can be more or less automatic and can involve different awareness levels.

Nevertheless, MCA has clearly shown that the factor effects were not so global but more complex: if most drivers (17 among 20 participants) displayed different behaviours according to the road geometry (see driver $Ac$ on Figure 5), three drivers displayed little differences ($Ib$, $Mu$ and $Ys$). These three drivers being not situated on Axis 1 right side, they seldom use the $o$ modality. One explanation may be that by keeping both hands on the low or intermediate parts of the wheel, for instance see Figure 7(a) for driver $Ys$, those drivers can use the same hand position strategy for all road geometries, regardless of the maximum angle of turn, thus without being forced to cross hands.

For the 17 other drivers (see for instance Figure 7(b)), the results showed an adaptation of the hand motion to the road geometries. Similar conclusions can be drawn from driving in dense traffic (Walton and Thomas 2005; De Waard, Van Den Bold, and Lewis-Evans 2010): as road geometry complexity increases (e.g. with large steering angles and/or succession of left/right turns), drivers put their hands on the top of the steering wheel, which is conducive to hand crossing. A difference with the steering wheel literature is that the one-hand position was rarely used on the steering wheel. This position was often observed in studies of hand position during road driving tasks involving less mental workload and less traffic (Walton and Thomas 2005; Jonsson 2011).

![Figure 12](image-url)
MCA has shown that individuals who displayed low changes from a road geometry to another (Ib, Mu and Ys), i.e. drivers who mainly used a strategy consisting in keeping both hands on the low or intermediate parts of the wheel, thus without being forced to cross hands, showed low changes from a repetition to another (see driver Mu on Figure D of the Electronic Appendix). On the opposite, drivers with large differences according to the road geometry factor also displayed large differences according to the repetition factor (see driver Ac in Figure D). Once again, positioning the hands and the medium or bottom parts on the steering wheel yields a rather stable strategy whatever the road geometry.

An additional result is worth noting concerning the high individual factor effect lined out by our descriptive study. Contrary to the Jonsson (2011) or Fourie, Walton, and Thomas (2011) studies, this effect was not linked to the driver’s gender (if the sex label is indicated for each point shown in Figure 6(a), the 20 individual points had random positions).

To go further in the study of the road geometry factor effect, a second analysis was performed using an inferential approach. This analysis was used with two SWs that played a pivotal role in the first analysis: o (The left hand is off the steering wheel which played a main role in Axis 1 control) and n (The left hand is on the right of the steering wheel which played a main role in Axis 2 control). The pairwise comparison tests showed significant differences for some road geometries (Figure 12). For instance, road geometry 7 (Figure 1) was the most aside in terms of o window use, see the left position of point o in Figure 6(b) and the four significant tests shown in Figure 12(a). Road geometry 7, which was the unique driving situation containing a succession of left/right bends with small slopes (involving a steering angle lower than 180°), did not require to move hands much and thus to cross hands. As a main consequence, this road geometry yielded a hand position strategy with rare cases where a hand was off the steering wheel (see road geometry 7 in Figure 3 bottom).

Road geometries 2 and 5 (Figure 1) were the most aside as regards modality n (Figures 6(b) and 12(b)). Among the seven road geometries, situations 2 and 5 were the only ones with a single right bend (with high maximum steering angle, i.e. about 300° and 400°, respectively). That is why modality n was often present (Figure 3).

With respect to the specific findings of the present experiment, a major problem was that results were validated using a tracking task, thus without any traffic, even though the scenarios were built from real driving situations, and the SID was given by a steering system major company (actually our industrial collaborator). De Waard, Van Den Bold, and Lewis-Evans (2010) have shown that additional traffic influences hand position during a lengthy highway driving task. So, additional experiments should be carried out with different parameters or conditions. For example, the mental workload of the tracking task could be increased (i.e. increased traffic, choosing different roads and so on) to assess whether there is an effect on the hand steering wheel position. However, our basic thesis concerning the use of a multivariate statistical analysis method was often present (Figure 3).

To go further onto the ecological validity of the present findings, let us now focus on the comparison between on-road and in-simulator driving. Most studies have mainly focused on task performance, such as speed control or lane keeping, and behavioural measures, such as eye movement or distance in between vehicles, e.g. in fog (Reed and Green 1999; De Winter et al. 2009; Wang et al. 2010). For instance, measures of lane-keeping performance showed that subjects drove with greater accuracy in the car than in the simulator, both the driver’s input to the vehicle (steering-wheel position) and the system output (lane position) showed larger variance in the simulator, but speed control measurements were comparable between the car and simulator (Reed and Green 1999). It is important to note that the absence or presence of correspondences reported in such studies was with a medium (good graphic environment but with a fixed base) or high fidelity simulator (dynamic base). Despite our very artificial task, it is sensible to think that the hierarchy found concerning the individual, road geometry and repetition effects on hand data could be validated with on-road situations (at about the same speed, i.e. 30 km/h), because the lack of optic flow, lack of vestibular motion feedback or reduced risk perception may have less influence on hand positioning than on more strategic data (lane keeping or headway). Such a hypothesis should be checked using a real driving environment.

In the future, we hope to use our approach with other participant samples (e.g. disabled drivers) and other data (e.g. electromyography activity). It might be interesting to know driver profiles for the purpose of offering ergonomic SID for disabled people.
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Supplemental data
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Notes
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