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Reducing speed and increasing neuromuscular stiffness

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How road narrowing impacts the trade-off between two adaptation strategies: reducing speed and increasing neuromuscular stiffness

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***Abstract*— When drivers encounter a road narrowing two potential adaptation strategies come into play that may increase safety margins: decreasing speed and increasing neuromuscular stiffness of the arms. These two adaption strategies have so far been studied in isolation. We expect that there is a trade-off between these two strategies, and that risk duration would impact a driver's selection of the trade-off. Specifically, we hypothesized that for a short risk duration, drivers will favour increased neuromuscular stiffness over speed reduction; and vice versa for longer risk durations. Twenty-six participants drove in a driving simulator and encountered different risk durations; realized by road narrowings (from 3.6 m to 2.2 m) of varying lengths (10 m, 100 m, 250 m, and 500 m). The neuromuscular stiffness was quantified by measuring the grip force exerted by both hands. The results show that all road narrowing conditions successfully induced driver adaptations, as a significant reduction in speed and increase in grip force was observed. However, the tested drivers did not consistently select the hypothesized different trade-offs for increasing duration of road narrowing: a low correlation was found between speed and grip force adaptations. Interestingly, individual trade-off were consistent: the within-subject variability in speed-grip force adaptations was low across the tested risk durations. Future research should further elucidate the underlying motivations for these individual adaptation strategies.**

I. Introduction

The ability to adapt is intrinsic to humans and imperative to cope with events in the driving scene. Literature provides evidence for different adaptation strategies across different experimental conditions, such as adapting speed, neuromuscular properties, and steering strategy when driving on different lane widths [1] [2] [3] [4]; adapting speed when approaching a curve [5] or a one-lane bridge [6]; adapting time headway and speed when driving in fog [7] or behind a lead vehicle [8]; and adapting steering strategy when perturbed by lateral wind gusts [9]. These voluntary adaptations to changes in driving scene and task demand can be accompanied by involuntary adaptations such as an increase in galvanic skin response (i.e., sweat production), heart rate, respiratory rate, pupil diameter, and eye scanning behaviour [10] [11].

The psychological mechanisms behind driver adaptations are yet to be elucidated. As Melman et al. (2018) argued, several theories have postulated that drivers exhibit a trade-off between two conflicting motivations, namely arriving at a destination in time (efficiency) versus avoiding dangerous situations (safety) [2], where the driver's level of subjective risk [12] [13], task difficulty [14], or time/safety margins [15] [16] are regarded as important homeostatic variables.

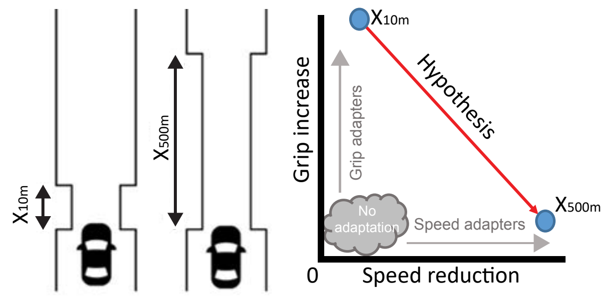

Figure 1. The hypothesized impact of the length of the narrow road section (x) on speed adaptation and grip force adaptation.

As indicated above, many researchers have shown the existence of steady-state driver adaptations, but few take the non-steady state and interaction between different driver adaptations into account. For example, a driving simulator study by Van der Wiel et al. [4] showed an increase in neuromuscular stiffness to reducing road width (2.5 m and 4.5 m) while driving at two different fixed speeds (70 and 120 km/hr). The authors of that paper suggested that in real life, it would be likely that drivers prefer to reduce speed and thereby reduce the need for the energy-consuming increase in neuromuscular stiffness. Although fixing the driving speed can be beneficial to reduce between-driver variability, it inhibits a realistic understanding of the interaction between driver adaptations. Additionally, most studies ([1]-[4]) use fixed lengths of narrow road sections which only allows for investigation of steady-state driver adaptations due to fixed risk durations. In this paper, we aim to investigate the non-steady state interaction between two commonly found adaptations strategies: speed and neuromuscular stiffness adaptations for different risk durations.

Speed adaptation has strong implications on road safety. In essence, higher speed reduces a driver's time to respond in an emergency scenario, increases the severity of the impact, and the probability of being involved in a crash [17] [18] [19] [20]. Adapting the neuromuscular stiffness improves robustness to perturbations but is an energy-consuming strategy [21]. Previous studies have estimated neuromuscular stiffness by adding perturbations on the steering wheel [4] [22] [23], or by measuring EMG signals which are intrusive and generally have low signal to noise ratio [24]. Previous studies reported an inverse relation between neuromuscular stiffness and grip force during driving [3] [25] [26], allowing for a non-obtrusive measurement with a good signal to noise ratio. These findings motivated us to use grip force measurements.

In this study, a decrease in road width was utilized to induce speed and neuromuscular stiffness adaptations, as a change in

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road width is known to cause drivers to adjust their driving speed [6] [1] [2] and neuromuscular stiffness [4] [3]. To investigate the interaction between speed and neuromuscular stiffness adaptations, we created different risk durations by exposing the driver to four different lengths of road narrowing.

In summary, this study examines to what extent the duration of increased risk (i.e., the length of a road narrowing) influences the drivers' speed and neuromuscular stiffness strategy (measured by grip force). We expect that there is a trade-off between these two strategies, and that risk duration would impact a driver's selection of the trade-off. Specifically, we hypothesized that for a short risk duration, drivers will favour increased neuromuscular stiffness over speed reduction; and vice versa for longer risk durations (Fig. 1).

II. METHOD

A. Participants

Twenty-six participants (9 female) 20 to 32 years old (*M* = 25.9, *SD* = 3.2) volunteered in this study. All participants had normal or corrected to normal eyesight and had a valid driver's license for at least one year (*M* = 6.5, *SD* = 3.4).

B. Apparatus

The experiment was conducted in a fixed-based driving simulator. The scenery was visualized using three LCD projectors with a horizontal and vertical field-of-view of 180◦ and 40◦. The simulation data was logged at 100 Hz. Vehicle dynamics were simulated with a single-track model (heavy sedan of 1.8m wide), with an automatic gearbox and self-aligning torques were imposed on the steering wheel. Car vibrations ('road rumble') were simulated with a seat shaker implemented in the driver's seat. During the experiment, participants could control the speed of the vehicle, and the speedometer was displayed on the dashboard.

The grip force was measured using Tekscan 4256E pressure sensors attached to gloves (Fig. 2). The sensor consists of 349 sensils (i.e., individual pressure-sensing locations) with a spatial resolution of 7.1 sensors/cm^2. During this study, the total sum of all sensils for the left and right hand were recorded. The grip force data was logged at 20 Hz and synchronized with the simulator data.

C. Road conditions and environment

During the experiment, participants drove 35 kilometres on a 3.6 m wide road. Participants encountered four different straight road-narrowing lengths (10 m, 100 m, 250 m, and 500 m). For each road-narrowing length, the road width reduced from 3.6 m to 2.2 m, allowing 0.9 m and 0.2 m lateral deviation on either side of the car, respectively (Fig. 2). Every participant drove the four road-narrowing lengths eight times, which were presented in a counterbalanced order. All road-narrowings occurred on a straight road section, and were preceded and succeeded by a 200 m wide section. The road narrowing sections were separated by straights and curves sections to allow the drivers to reach their preferred speed. Speed perception was enhanced by means of trees alongside the road. Cones were placed along the entire road, and a car front was visualized to facilitate perception of the car's position relative to the road boundaries. A vibration that mimicked rumble strips was implemented on the steering wheel to give additional feedback to the driver when the car

Figure 2. The used grip force sensors (left), and the simulator environment (right) for the 500m road narrowing including the car front.

was outside the lane boundary. A multi-sine torque perturbation consisting of 6 low frequencies (ranging from 0.25 to 18 Hz) was applied to the steering wheel to mimic environmental disturbances (e.g., wind) that require the participants to steer even on long straight sections. The total multi-sine was scaled to low torques (M = 0, SD = 0.13 Nm) to ensure that the driver was not disrupted during driving due to the perturbation.

D. Experimental procedure

Before the start of the experiment, the grip sensors were calibrated using a bulb shaped dynamometer, which ensured a good pressure distribution over all sensils. Participants were instructed to apply a force of 5 kg, 10 kg, 15 kg and a maximum force to the hand dynamometer. To get familiar with the driving simulator, each participants performed a training trial of 7 minutes on the wide road with no lane narrowing. During the experiment participants were instructed to drive as they normally would do while not hitting any cones, and to keep their hands in a 10-to-2 position. The experimenter stood next to the participants during the experiment and after each narrow section, the participants answered the question: '*How much effort did it cost you to successfully drive this section?'*. Participants responded with a number between 1 (for no effort) and 10 (for a lot of effort). In total the experiment took approximately 1 hour.

E. Dependent measures

For all dependent measures, the wide section metric was calculated between 200 m to 150 m before the road narrowing starts. The narrow road is calculated over the middle 5 meters of the narrow road section.

1) *Effect of road width*
- *Mean speed* [km/h]: The mean speed was calculated over all 32 wide sections combined and over all 32 narrow sections combined.
- *Mean grip force* [N]: The mean grip force of both hands combined was calculated over all 32 wide sections combined and over all 32 narrow sections combined.

2) *Effect of road width length*
- *Delta speed* (km/h; ΔSpeed): The mean speed difference between the wide section relative to the narrow section.

- *Delta grip* (N; ΔGrip force): The mean grip force difference between the wide section relative to the narrow section.
- *Self-reported task effort* (1-10; SRTE): After each narrow section, the participants reported how much effort the current task takes from 0 (no effort) to 10 (a lot of effort).
- *Time off-road* (s): The amount of time for which the car was outside the cone boundaries for the narrow road section

F. Statistical analysis

For each dependent measure, the mean of all eight repetitions was computed. These values were collected in a 26 x 4 matrix (26 participants and 4 road width lengths). First, the matrix was rank-transformed according to Conover and Iman [27], to account for possible violations of the assumption of normality. This rank-transformed matrix with values ranging from 1 to 104 was submitted to a repeated-measures ANOVA with the four narrow-road lengths as a within-subject factor. A post-hoc paired t-test was performed with Bonferroni corrections applied to the six pairwise comparisons between the narrow road lengths. To investigate the effect of road width (section E.1), a paired t-test was used, after rank-transformation (i.e., with values ranging from 1-52).

III. Results

Figure 4 shows the lateral position, speed, and grip force averaged over all participants, for the entry (200 m before road narrowing), narrow section, and the exit (200 m after road narrowing). At the entry, the 10 m road narrowing results in slightly delayed and less speed reduction compared to the three longer narrow road lengths. An increase in grip force can be seen for all four conditions before entering the narrow section. Drivers maintain an almost constant speed, and a constant grip force over the entire narrow road section, with a small increase and decrease at the start and end of the section. At the exit, drivers increased speed and decreased grip force to approximately the speed at which they drove before they entered the entry section.

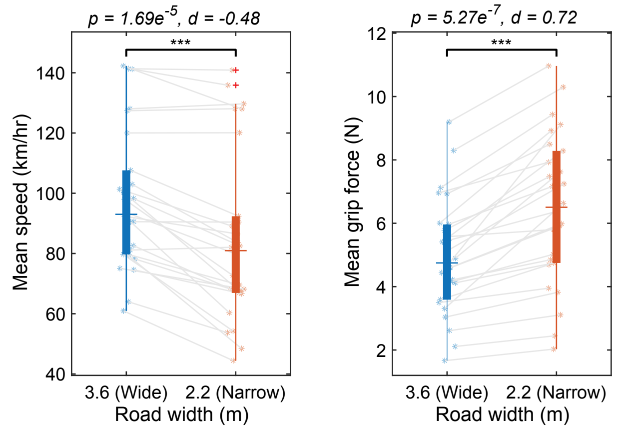

Figure 3. Mean speed (left) and mean grip force (right) effect for all participants (asterisks) for the wide and narrow sections (i.e., all four narrow road lengths combined). Where significant differences, ***: $p<0.001$, and *d:* Cohen's *d.*

A. Effect of road width

The mean speed and mean grip force for all 32 wide combined and 32 narrow sections combined are shown in Fig. 3. Participants drove with a lower mean speed and had a higher grip force on the narrow roads as compared to the wide roads. Confirming that road width reduction is indeed a good method to induce speed and grip force adaptations.

B. Effect of narrow road length

Figure 5 visualizes the results for the four dependent measures, including the individual results for each participant averaged over eight repetitions. The results of the repeated-measures ANOVA show a significant effect for the narrow-road length for all four dependent measures. The post-hoc analysis identified a significantly smaller speed reduction for the 10 m compared to the 100 m section only. The grip force increment was lower for the 10 m than for the 100 m, 250 m and 500 m section. No significant differences were found for ΔSpeed, ΔGrip force between the other narrow road lengths. The SRTE and time off-road progressively increased with narrow road lengths; between all narrow road lengths comparisons.

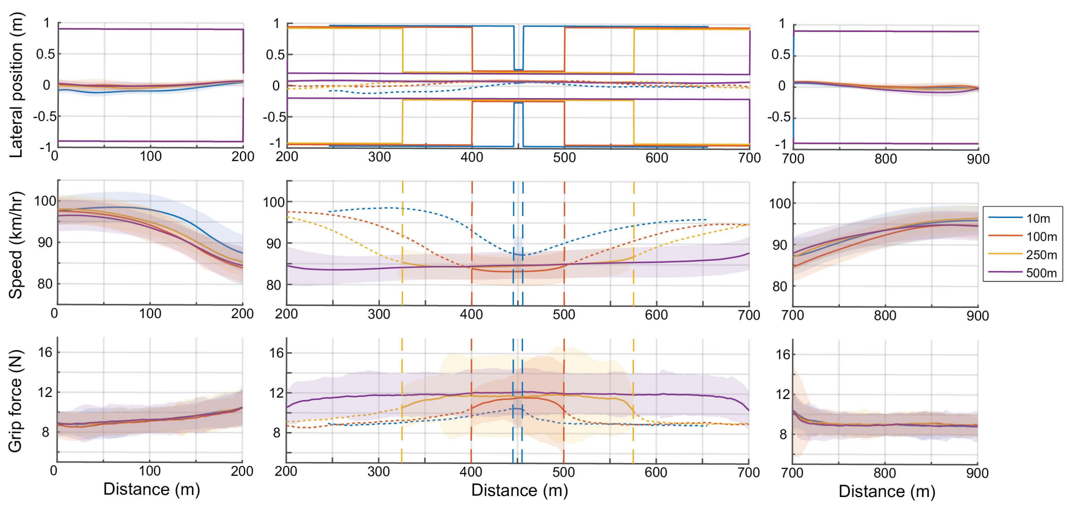

Figure 4. Mean results (solid), and standard deviation (transparent) for all participants for all four conditions as a function of the travelled distance. The top panels show the lateral position along with the lane width, the middle panels the speed and the bottom panels the grip force. The left panels show the entry section, the middle panels the narrow road section centred in the middle of each road narrowing and right panels the exit section.

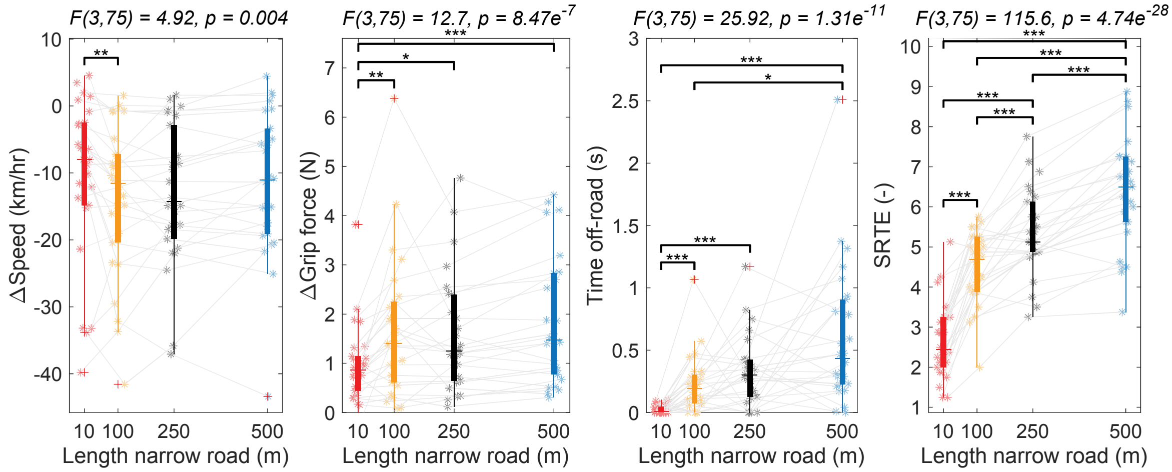

Figure 5. Boxplots for the four narrow road lengths for all participants (asterisks). From left to right: ΔSpeed, ΔGrip force, time off-road and self-reported task effort (SRTE). Brackets indicate significant differences, *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$.

C. Interaction between speed and grip force adaptation

Figure 6-left shows a scatter plot of ΔSpeed and ΔGrip force. A small positive correlation (ρ = 0.15) was found, suggesting no trade-off between speed and grip force adaptations. Figure 6-middle visualizes the individual strategies adopted by all participants between 10 m and 500 m, Different individual strategies can be identified; for example, some drivers mainly adapted their speed (e.g., participant no. 4, 11, 26, 25; visualized with a red line in Fig. 6-middle with an abs slope < 0.03), some adapt only grip force (e.g., participant no. 7, 15, 17, 21; visualized with a green line in Fig. 6-middle with an abs slope > 0.5), adapt both speed and grip force (e.g., participant no. 13, 22, 16, 14), whereas others show minimal adaptation (e.g., participant no. 3, 5, 6, 10).

Figure 6-right shows the mean and the standard deviation (SD) over the eight repetitions for the 100 m condition for each driver. Compared to the inter-subject variability (i.e., 100 m SD: ΔSpeed = 11.3 km/hr, ΔGrip force = 1.42 N), a lower intra-subject variability was found (i.e., 100 m mean SD: ΔSpeed = 6.7 km/hr, ΔGrip force = 1.25 N). This indicates that the individual participants adopted consistent strategies within themselves.

D. Learning effect due to repetitions

The effect of the repetition order of the experiment is shown in Fig. 7 for the lateral position, speed and the grip force as a function of the travelled distance averaged over all participants for each repetition. When drivers become more familiar with a driving task they increased their speed and decreased their grip force. In the 10 m section, the highest speed is observed for the 8th repetition and the grip force decreases over the eight repetitions averaged over all participants, indicating a learning effect.

IV. Discussion

In this driving simulator study, we expected that there would be a trade-off between two adaptation strategies (speed and neuromuscular stiffness), and that the risk duration would impact a driver's selection of the trade-off. Specifically, we hypothesized that for a short risk duration, drivers will favour increased neuromuscular stiffness (operationalized by grip force) over speed reduction; and vice versa for longer risk durations (Fig. 1).

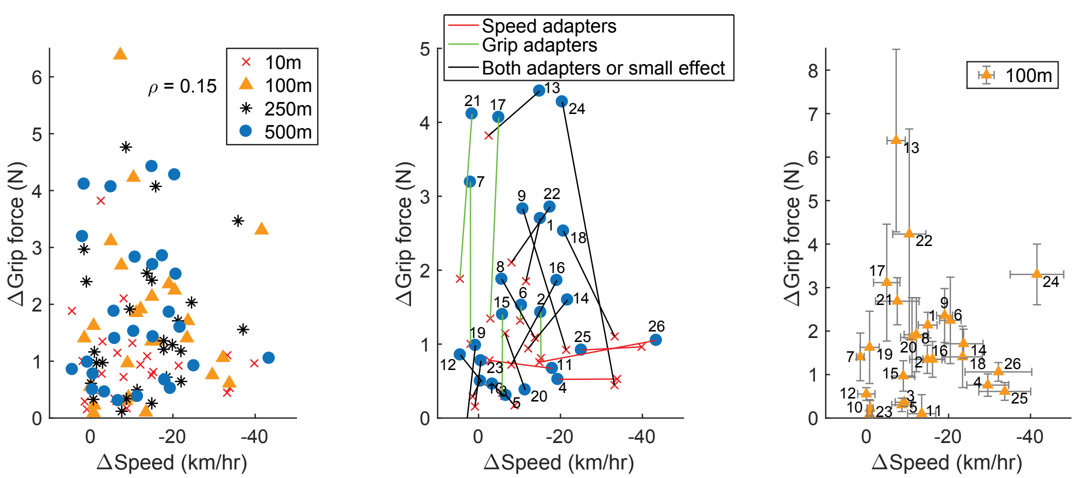

Figure 6. Left: a scatter plot of ΔGrip force and ΔSpeed for the four different road narrowing lengths. Middle: visualizes the adaptation between the 100 m and 500 m narrow road length. Speed adapters and grip force adapters are visualized by red (abs slope < 0.03) and green lines (abs slope > 0.5), respectively. Right: The mean (triangle) and the standard deviation (error bars) over all the 8 repetitions on the 100 m section for each driver.

Our results showed that road width manipulation was successful in evoking speed and grip force adaptations: participants reduced speed and increased grip force when road width reduced (Fig. 3 and Fig. 5), which is in accordance to literature [2] [3] [4]. However, only a low positive correlation was found between the two adaptation strategies across drivers (ρ = 0.15), indicating that no trade-off exists. A possible reason for the apparent lack of trade-off may be due to the large variety in individual adaptation strategies that are consistently adopted by each driver. As visualized in Fig. 6-middle some drivers adapt as hypothesized (Fig. 1) with an increased speed and decreased grip force, whereas others adapt only speed, grip force or show minimal adaptation. Participants showed to be consistent within their own adaptation strategy, over the eight repetitions of each narrow road section (Fig 6-right). The large inter-driver variability and consistent intra-driver choice for adaptation strategies points towards an ecological fallacy [28], indicating that conclusions about the behaviour of an individual should not be made based on the results of the entire group.

The results also showed that longer narrow road sections were subjectively perceived more effortful and objectively performed worse (i.e., higher time off-road; Fig. 5). Interestingly, the adaptation strategies that could be utilized to reduce the task difficulty (i.e., reduce the speed) or to be more robust to perturbations (i.e., increase grip force), seem to have been sparingly employed by most drivers.

One could argue that the fact that this study was performed in a fixed-base driving simulator, which has the advantage of the ability to perform many repetitions in a consistent environment, but lacks physical risk and has limited speed and depth perception, might explain the limited effect of speed and grip force adaptions (Fig. 5). However, this is unlikely, as strong speed and grip force adaptations (Fig. 3) were found between the wide and narrow road sections. Similar adaptations were also found in on-road experiments [29] [30]. Additionally, the relative validity (i.e., the effect sizes between the pairwise comparisons) is high for simulators [31].

We also reflected on whether the lengths of the narrow road section might have been insufficient to investigate the trade-off. The average time a driver drove on the narrow section was approximately 25 s, which could have been insufficient to cause discomfort for the driver to stimulate a change in the adaptation strategy. This is supported by the observation in Fig. 5, where the SRTE is still increasing and has not reached a steady-state value. This suggests that larger road narrowing lengths should be investigated to examine the trade-off hypothesis. The only difference in speed and grip force adaptations were found with respect to the 10 m section. Figure 4 and 5 revealed a different entrance strategy and less speed reduction and grip force increase, for the 10 m section compared to the longer road sections. This could suggest that drivers decide their strategy (positioning, speed, and grip force adaptation) before entering the narrow section and hence the length of the section had little effect on their adaptation behaviour.

Previous literature has shown that when drivers become more familiar with a driving task they increase their speed

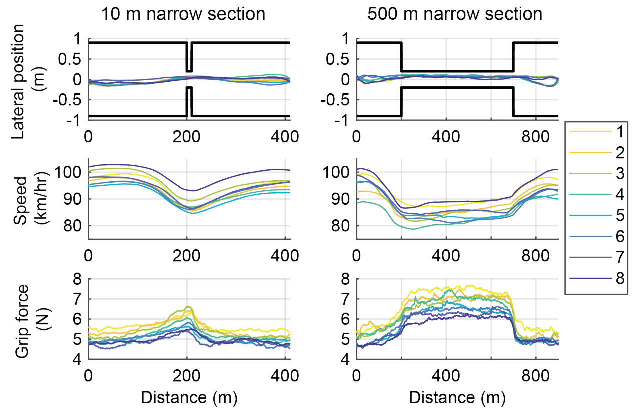

Figure 7. The lateral position, speed and grip force for each repetition averaged over all participants for the 10m (left), and the 500m narrow road section (right).

[32]. Such a learning effect in speed was found in this study, along with a reduction in the grip force over the eight repetitions averaged over all participants (Fig. 7). A similar effect in neuromuscular property changes using electromyography (EMG) was observed in non-driving [33] and driving [34] tasks. However the grip force sensor output degraded over time which could also have influenced the results [35]. In short, the grip force demonstrates itself to be a promising non-obtrusive method to capture neuromuscular adaptations as long as the sensor degradation is mitigated via calibration.

Although further investigation is needed to understand if longer narrow road sections were required to evoke a coherent trade-off across participants, the fact that participants adapted their speed and grip force to road narrowing, and adopted consistent individual strategies highlights the possibility of an ecological fallacy and the importance of investigating the interaction between adaptation strategies on an individual level. All-in-all the quest for better understanding steady-state and non-steady state driver adaptations, their interaction, and their underlying mechanisms continues.

V. Conclusions

- The interaction between different driver adaptation strategies is a seldom studied topic.
- Road narrowing is an effective method to induce speed and grip force adaptations (Fig. 3).
- The twenty-six drivers did not consistently select the hypothesized trade-off for increasing duration of road narrowing: a low correlation was found between speed and grip force adaptations (Fig. 6).
- Individual trade-off were consistent: the within-subject variability in speed-grip force adaptations was low across the tested risk durations (Fig. 6).
- Grip force measurement is a novel and non-obtrusive way to quantify neuromuscular stiffness adaptations.
- The results highlight the possibility of an ecological fallacy and the importance of investigating the interaction between adaptation strategies on an individual level.

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