How does a symmetrical steering wheel transformation influence the take-over process?

Philipp Kerschbaum[1], Kamil Omozik[1], Patrick Wagner[2], Sophie Levin[2], Joachim Hermsdörfer[3], & Klaus Bengler[4]
[1]BMW Group, [2]Former BMW Group Research & Technology,
[3]Department of Sport and Health Sciences, Technical University of Munich,
[4]Department of Mechanical Engineering, Technical University of Munich, Germany

Abstract

During the last several years, numerous studies have been published regarding the human factors challenges in vehicle automation. For conditional automation (SAE, 2014), vehicles must support the driver at non-driving related activities during automated driving as well as manual driving. Both activities have conflicting requirements regarding the vehicle interface, especially for the steering wheel. In order to solve this conflict, Kerschbaum et al. (2015) introduced the idea of changing the steering wheel shape depending on the active driving mode. However, it turned out that the asymmetrical transformation process which is based solely on rotating joints applied in that study prolonged the time drivers needed to take over control from the automation. In this paper, the investigation of an alternative technical solution is presented which allows a symmetric transforming motion of the steering wheel rim. The system was tested in a high fidelity driving simulator study with different take-over scenarios; a state-of-the-art steering wheel served as the control condition. It turned out that the symmetrical transformation indeed influences gaze- and motion reaction parameters, but contrary to the asymmetrical transformation, the main effects are rather positive.

Motivation

In the near future, conditional automation (SAE, 2014) of the driving task is expected to be available for passenger vehicles. At this level of automation, the driver may withdraw from the driving task completely when certain conditions are met. Still, the driver must be ready to take over control should the automation reach a system boundary. In this case, it triggers a take-over request (TOR) while the driver is still provided with a sufficient amount of time to take over. Regarding the human factor of conditional automation, numerous studies have been conducted during the last decade (e.g. see Gold et al., 2013; Lorenz et al., 2014; Merat et al., 2014; Naujoks et al., 2014). Generally, conditional automation requires the vehicle to allow the following three tasks for the driver:

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- Automated driving while dealing with non-driving related tasks. In case this task involves a display in the vehicle, the driver should ideally have free access to it when seated in physiologically neutral body posture. In this position, comfortable interaction is also possible during long-term automated drives.
- Manual driving. For lateral guidance of the vehicle, the round-shaped steering wheel is commonly applied in modern vehicles.
- The transition between these modes, especially from automated to manual driving if requested by the automation (also referred to as 'take-over situation' in the following). This transition implies the redirection of visual attention, manual regaining of control and taking over based on rebuilt situation awareness (Endsley & Kiris, 1995; Gold et al., 2013)

Automated driving and manual driving result in competing requirements for the vehicle cockpit, especially the steering wheel (cf. Kerschbaum et al., 2015). The static round-shaped rim is a valid option for manual driving. However, it blocks the space right in front of the driver which is valuable for the allocation of displays and controls optimal for non-driving related activities during automated driving. This goal conflict may be solved due to physical transformation of the steering wheel rim when changing the driving mode. This is a salient change of the cockpit geometry, and especially the re-configuration of the circular shape in take-over situations has the potential to accelerate the driver reaction. However, it must not hinder the driver in any way during the transitions between the driving modes.

The experiment reported by Kerschbaum et al. (2015) revealed that an asymmetrical transformation of the steering wheel indeed has influence on the transitions. It decreases the time until drivers start moving after the TOR while it prolongs the take-over time in certain take-over situations. Generally it remained unclear if the results were affected by the unusual asymmetric motion of the rim segments and the investigation of symmetrical transformation seemed relevant in this context. For this reason, a study was conducted in the high fidelity driving simulator of BMW Group Research & Technology focusing on take-over situations. In this study, a symmetrically transforming steering wheel ("TSW") was compared to a state-of-the-art steering wheel (control condition, "CC"). The following research questions need to be answered:

- Is there any influence of a symmetrically re-transforming steering wheel on the guidance of visual attention after a TOR?
- Is there any influence of a symmetrically re-transforming steering wheel on the motoric regaining of control after a TOR?
- Are there any associated effects of a symmetrically re-transforming steering wheel regarding the manual driving task after the transition from automated driving?

Method

Concept and hypotheses

The symmetrically transforming steering wheel was implemented with four rotating joints in the rim, separating it in four segments. The upper segment was equipped with a telescopic element. When driving in automated mode, all upper segments moved downwards and allowed free prospect to the instrument cluster display. In case of a TOR, they symmetrically moved upwards and form a round-shaped rim as known from modern vehicles within less than one second. During manual driving mode, the steering wheel remained circular and stiff. The process of symmetrical re-transformation during the transition task from automated to manual driving mode is illustrated in Figure 1.

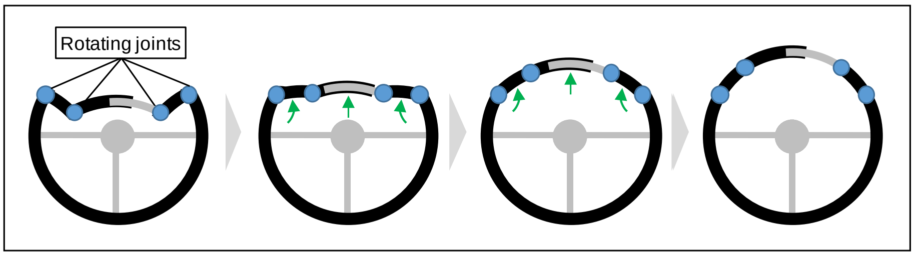

Figure 1. Symmetrical transformation process.

The physical, symmetrical movement of the steering wheel rim segments enhanced the TOR warning signal at take-over situations which was expected to lead to a quicker redirection of visual attention of drivers towards the driving scene. Consequently, the gaze reaction times were believed to be influenced which includes the first saccadic reaction and the time span until drivers have their eyes on the road after the TOR. An additional hypothesis was that the enhanced warning signal influenced the hand movement reaction of drivers. In contrary to the experiment with the asymmetrical transformation, this potentially includes the hands-on times as the symmetrical transformation process is smooth, visually balanced and therefore less distracting during the transition task. It still might shortly attract the driver's attention (Yantis & Jonides, 1984), and make drivers hesitate after their initial start of movement. Regarding the take-over time and the manual driving quality after the transition, no hypothesis could be derived from literature or former experiments. However, the corresponding data was analysed because any detrimental effect would be highly important when discussing the symmetrical transformation of the steering wheel rim. Besides the steering wheel concept, the driver interface of the mock-up vehicle was kept simple: the active driving mode was illustrated by coloured icons in the instrument cluster display. In case of a TOR, a clearly audible tone and a red icon warned the driver to take over control.

Experiment design

In order to ensure the participant's safety, a high fidelity driving simulator was chosen for the experiment which allows participants to experience kinaesthetic feedback while driving. The mock-up car was a 2010 BMW 5 Series equipped with all required mirrors and a full simulated driver interface including visual displays and sound. The original steering wheel of the mock-up car was exchanged with a steering wheel prototype which was able to implement the symmetric transformation of the rim. As illustrated in figure 1, it had four rotating joints integrated and a custom-made telescopic element at the top. This element could change its length along the circular trajectory of the original steering wheel rim. The core structure of the prototype was made of stainless steel, the next layer was formed by 3d-printed parts. Microcellular rubber was integrated to create a comfortable feeling when touching and grasping the rim. The entire rim was additionally covered with a ductile fabric. The required force for transforming the steering wheel was generated by a linear actuator in the motor compartment and transmitted through the dashboard to the steering wheel by steel cables. Due to this solution, the driver could not hear the actuator noise which was found to be one possible influence on the results reported for the asymmetrical transformation (cf. Kerschbaum et al., 2015). The built-in controller in the actuator was programmed to limit the applied force for safety reasons, the software to control the actuator was implemented on a microcontroller.

The driving simulator allowed participants to drive on a virtual highway with three lanes and one emergency lane. It provided ordinary straight segments and curves. On the virtual highway, event areas were implemented at which specific driving situations could be generated for the driver. Regarding the research questions explained above, two take-over situations were defined. In situation ‘A’, the driver was prompted a TOR while driving on the right lane on straight track (cf. Kerschbaum et al., 2015). At the same moment when the TOR occurred, two crashed cars became visible on the right lane with TTC=7s for the driver to react. The left lane was blocked by traffic cars, so the driver could only swerve to the middle lane or brake after taking over in order to avoid an accident. In situation ‘B’, a TOR was prompted but there was no immanent risk for the driver to collide. The road ahead was free. This situation simulated a TOR due to an internal technical problem of the automation. It was integrated in order to investigate the driver reactions with no extrinsic motivation to react. Additionally, situation ‘T’ (traffic) was implemented. Here, the vehicle approached a traffic jam while driving in a curve. Again, a TOR was triggered with TTC=7s for the driver to brake and avoid a crash. The aim of situation T was to increase the variety of situations and therefore eliminate learning effects. Because no steering maneuver was necessary, situation T was not adduced for data analysis. In order distract participants from the driving scene before the TOR, they were provided with a simple game in all take-over situations. It was displayed on the instrument cluster screen and controlled with a control unit in the middle console of the mockup vehicle. The game popped up at random times, but always before a TOR occurred. The driving situations are depicted in Figure 2.

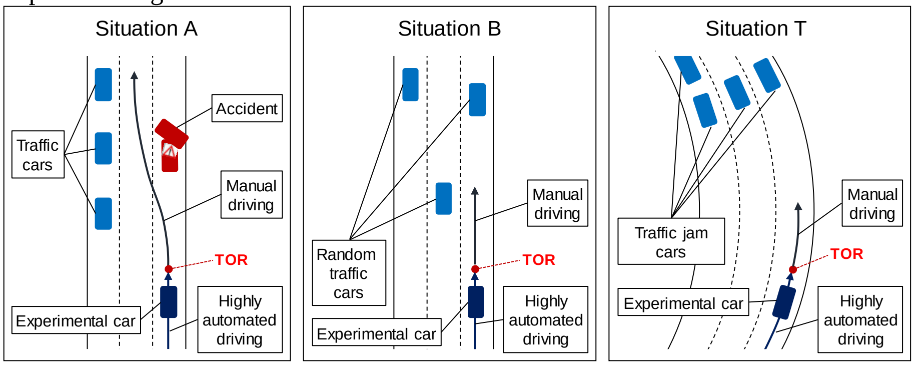

Figure 2. Schemes of the driving situations A (cf. Kerschbaum et al., 2015), B and T.

Regarding the experimental procedure, 62 employees of the BMW Group took part in four consecutive drives. The goal of the first test drive was to familiarize the participants with the driving simulator environment. Only manual driving mode was available with no traffic cars on the highway. In the second test drive, participants could get used to the automated driving mode. With a button on the dashboard, automation could be activated, deactivating was possible by steering, braking or using the button again. On the highway, there were traffic cars and for two times, situation A occurred. This allowed to get participants used to the TOR warning signal and the requirement to engage in manual driving afterwards. In the following, a repeated measures design was implemented with the two within-factors ‘steering wheel concept’ and ‘take-over situation’. Two more experimental drives were executed, one with the transforming steering wheel, one with the control condition concept. In both drives, situation A occurred three times, situation B twice. This distribution was chosen because in situation A, participants were required to engage in a time-critical steering maneuver which was most difficult for the measurement systems to capture without errors. Situation T was not utilized for the comparison of the steering wheel concepts as explained above and therefore interspersed only once. The order of occurrence regarding both factors was permuted to avoid sequence effects. The steering wheel concept which was provided in the first experimental drive was also used in the preceding test drive.

Operationalization

The dependent variables chosen to answer the research questions above are identical to the experiment reported by Kerschbaum et al. (2015). The gaze reaction time (variable t_{gaze}) describes the time span from TOR until the first saccadic reaction of drivers. The road fixation time (variable t_{road}) describes the time span until drivers fixate the driving scene after TOR (see also Gold et al., 2013). Gaze data was recorded with eye-tracking glasses (‘Dikablis’). Regarding the driver’s hand movement, the first movement reaction (variable t_{move}) and the time span until drivers have their hands on the steering wheel (variable $t_{hands\text{-}on}$) after TOR are calculated. Movement data was recorded using an optical motion capturing system (‘VICON’ Bonita B10) with seven cameras. Therefore, passive markers were glued onto the drivers’ hands and fingers. In order to allow the tracking of the driver’s hands even behind the steering wheel, two of the cameras were mounted onto an aluminum frame on the top of the vehicle mockup. They observed the driver’s hands through the windshield. The setup is depicted in figure 3.

Figure 3. Motion tracking systems implemented in the mock-up vehicle.

The driving simulator was able to record the driving data of the vehicle, including position on the road, accelerations in lateral (variable a_{lat}) and longitudinal (variable a_{long}) dimension, and manipulation of the brake pedal and steering wheel. Hence, the variables a_{res} and also $t_{take\text{-}over}$ could be derived based on the procedure reported by Gold et al. (2013). In all take-over situations, data recording was started at the moment of the TOR and stopped 20 seconds after the TOR or as soon as the vehicle passed the accident in situation A. For the recurring situations A and B, average values were calculated for the statistical analysis.

Results

Due to technical problems e.g. with either the driving simulator network, driving situations or the vehicle mock-up, 20 driving situations could not be analysed and were excluded. In the following section, the experiment results are reported separately for the guidance of visual attention, motoric regaining of control and the actual take over after the TOR.

Guidance of visual attention

In the take-over situations, the moment of the visual warning signal and warning tone slightly differed from the moment when the steering wheel re-transformed to a circular shape at 28 participants. This issue was due to latency problems within the driving simulator network. The corresponding data sets were excluded from analysis. Figure 4 displays the box-whisker diagrams regarding t_{gaze} and t_{road}.

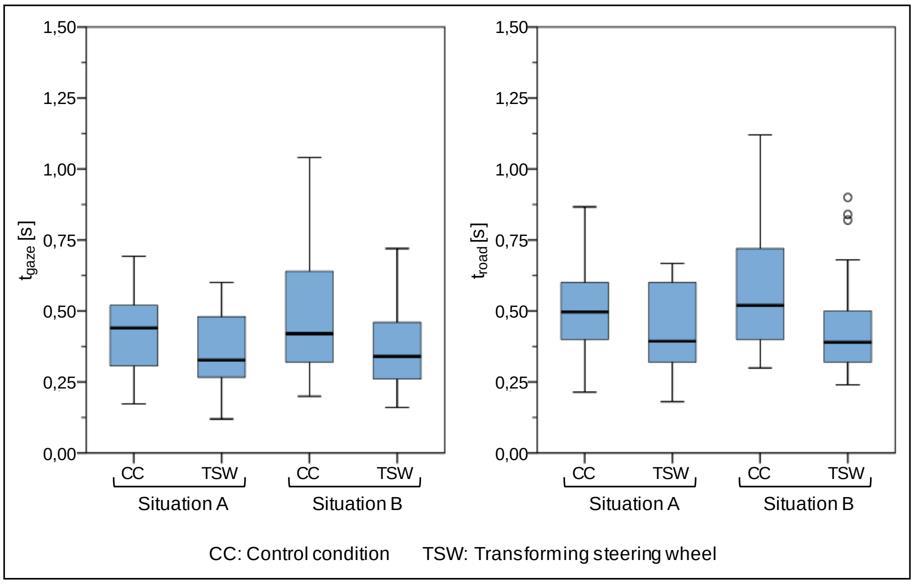

Figure 4. Box-whisker diagrams of t_{gaze} and t_{road}

The diagrams show that the average gaze reaction times are slightly shorter with the symmetrically transforming steering wheel compared to the control condition. This also becomes apparent in the descriptive statistics outline depicted in table 1.

Table 1. Results for t_{gaze} and t_{road}.

Variable	*Situation*	*CC*	*TSW*	*N*
Gaze reaction t_{gaze} [s]	A	M=0.42, SD=0.14	M=0.36, SD=0.14	18
	B	M=0.46, SD=0.21	M=0.38, SD=0.17	
Road fixation t_{road} [s]	A	M=0.51, SD=0.16	M=0.43, SD=0.15	18
	B	M=0.58, SD=0.23	M=0.47, SD=0.20	

A two-way repeated measures analysis of variance was conducted with the data to find out if the differences are statistically significant. The assumption of sphericity was met (Mauchly's test). The analysis revealed a significant effect regarding the steering wheel factor for t_{gaze} ($F(1,17)=8.469$, $p=0.01$, $r=.553$) as well as t_{road} ($F(1,17)=11.848$, $p<0.01$, $r=.641$). Regarding the situation factor, no significant main effects were found for t_{gaze} ($F(1,17)=1.230$, $p=0.283$) and t_{road} ($F(1,17)=2.494$, $p=0.133$).

Motoric regaining of control

During the experiment, several participants lost their passive markers and could not be tracked as planned originally. In several cases, the also turned their hands in a way which did not allow tracking or at least decreased the tracking quality. The corresponding data sets were additionally excluded from analysis, the number of included participants is given in table 2. The box-whisker diagrams of the variables

t_{move} and $t_{hands\text{-}on}$ are depicted in figure 5.

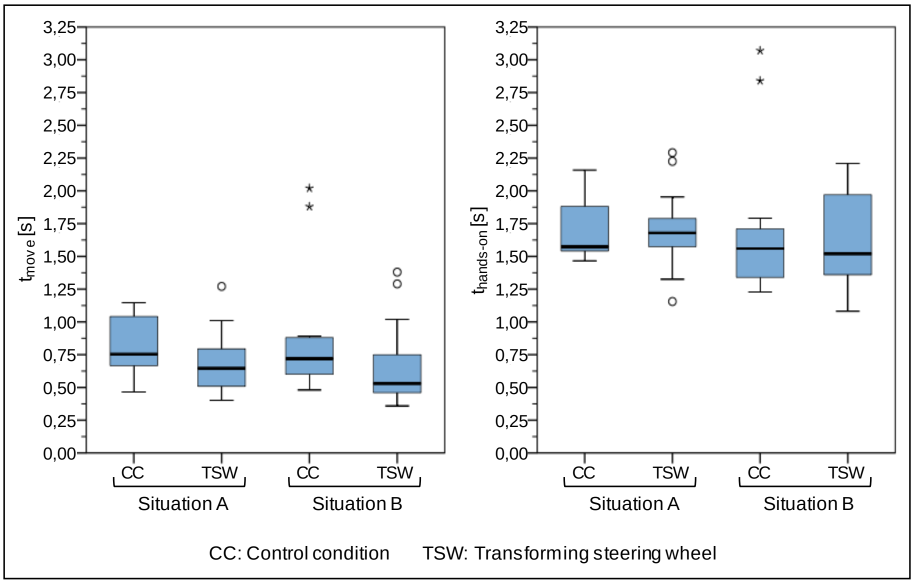

Figure 5. Box-whisker diagrams of t_{move} and $t_{hands\text{-}on}$

Regarding the variable t_{move}, the symmetrically transforming steering wheel led to a slight decrease compared to the control condition as visible in the corresponding box-whisker diagram. Table 2 shows the descriptive statistics.

Table 2. Results for t_{move} and $t_{hands\text{-}on}$.

Variable	*Sit.*	*CC*	*TSW*	*N*
Movement time t_{move} [s]	A	M=0.80, SD=0.22	M=0.70, SD=0.24	14
	B	M=0.87, SD=0.48	M=0.67, SD=0.33	
Hands-on time t_{hands_on} [s]	A	M=1.71, SD=0.24	M=1.70, SD=0.31	14
	B	M=1.70, SD=0.56	M=1.64, SD=0.35	

The assumption of sphericity was met for the data (Mauchly's test). A two-way repeated measures analysis of variance turned out that t_{move} is significantly shorter on average with the transforming steering wheel compared to the control condition (F(1,13)=4.781, p=.048, r=.474). No significant main effect was found for $t_{hands\text{-}on}$ (F(1,13)=0.185, p=.674). Regarding the situation factor, no significant main effects were found for t_{move} (F(1,13)=0.106, p=.750) and for $t_{hands\text{-}on}$ (F(1,13)=0.558, p=.468).

Taking over

Regarding the actual take-over, results of the accelerations and the take-over time are analyzed in the following section. The box-whisker diagram in figure 6 shows that in situation B there are six outliers with high take-over times.

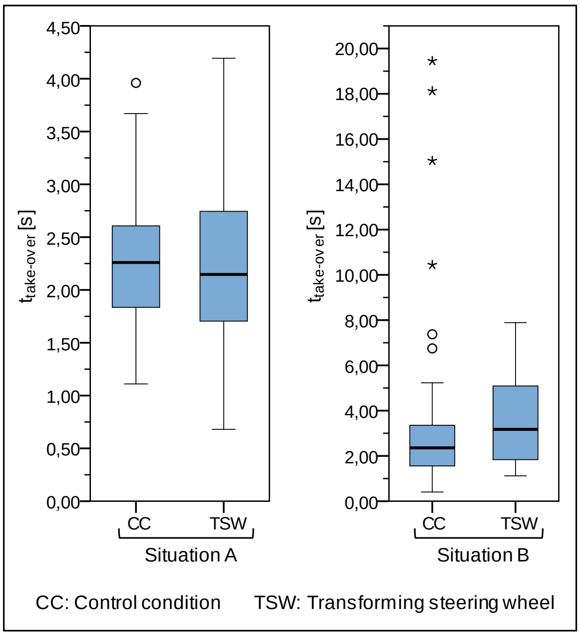

Figure 6. Box-whisker diagram of $t_{take-over}$.

These outliers are all associated with the control condition concept. The symmetrically transforming steering wheel does not evoke such outliers, all take-over times are below eight seconds. Table 3 gives an overview of mean and standard deviation values.

Table 4. Results for $t_{take-over}$.

Variable	*Sit.*	*CC*	*TSW*	*N*
Take-over time $t_{take-over}$ [s]	A	M=2.29, SD=0.66	M=2.24, SD=0.76	48
	B	M=3.56, SD=4.11	M=3.68, SD=1.98	

In a two-way repeated measures analysis of variance, the steering wheel turned out to have no significant effect on the take-over time ($F(1,47)=0.017$, $p=.897$). Because results showed a high difference between the two take-over situations A and B, the influence of the driving situation factor was analyzed in addition. It turned out to be highly significant ($F(1,47)=14.399$, $p<0.001$, $r=.471$). The assumption of sphericity was met for the data (Mauchly's test). The vehicle accelerations during the transition phase after the TOR are illustrated in box-whisker diagrams in figure 7.

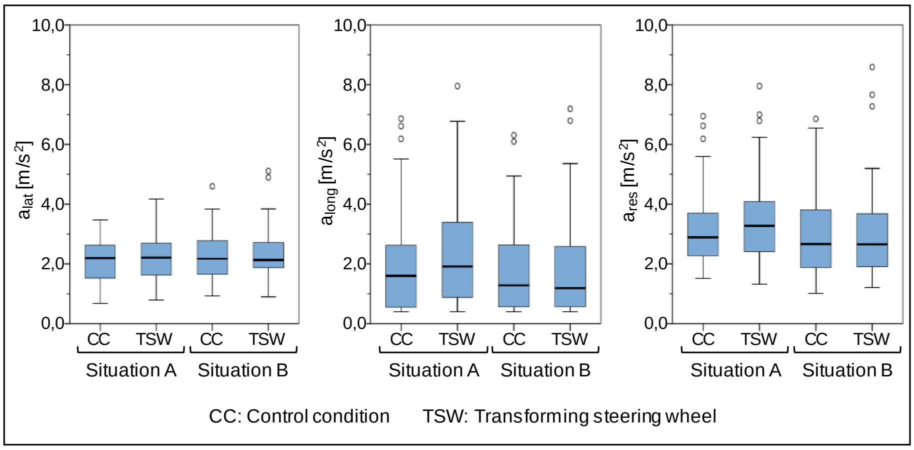

Figure 7. Box-whisker diagrams of a_{lat}, a_{long} and a_{res}.

In the box-whisker diagrams, acceleration levels in lateral and longitudinal dimension are similar. This mainly manifests in the mean and standard deviation values given in table 4.

Table 4. Results for a_{lat}, a_{long} and a_{res}.

Variable	*Sit.*	*CC*	*TSW*	*N*
Max. lateral acceleration a_{lat} [m/s^2]	A B	M=2.11, SD=0.71 M=2.27, SD=0.81	M=2.18, SD=0.74 M=2.28, SD=0.85	48
Max. longitudinal acceleration a_{long} [m/s^2]	A B	M=2.12, SD=1.76 M=1.86, SD=1.63	M=2.40, SD=1.86 M=1.87, SD=1.71	48
Max. resulting acceleration a_{res} [m/s^2]	A B	M=3.17, SD=1.31 M=3.02, SD=1.47	M=3.42, SD=1.46 M=3.03, SD=1.62	48

The two-way repeated measures analysis of variance did not reveal any significant effects. This applies to the lateral acceleration (steering wheel factor: $F(1,47)=0.346$, $p=.559$; situation factor: $F(1,47)=2.791$, $p=.101$), the longitudinal acceleration (steering wheel factor: $F(1,47)=0.614$, $p=.437$, situation factor: $F(1,47)=2.579$, $p=.115$). Hence, neither steering wheel nor situation factor had influence on the resulting acceleration (steering wheel factor: $F(1,47)=0.798$, $p=.376$, situation factor: $F(1,47)=1.548$, $p=.220$).

Discussion

On the contrary to the asymmetrical transformation concept, the symmetrical version has a statistically significant positive effect on the gaze behaviour of drivers in take-over situations. Visual reaction times are shorter regarding both the initial reaction as well as the fixation of the road. Hence, drivers may start to analyse the environment earlier and potentially have more time to react until the vehicle reaches the system limit of the automation.

Similar to the initial visual reaction, drivers also start moving significantly earlier on average with the symmetrically transforming steering wheel. While it was found for the asymmetrical transformation that this time advantage is lost during the transition process and drivers take over later, this is not necessarily the case with the symmetrical transformation. No significant effect could be found here. Hence, the actual realization of transformation indeed changes the way drivers interact with the automation. It acts as an additional, salient cue for participants in take-over situations as it partially accelerates the reaction times. Additional insights specifically regarding the movement reaction might be found due to a detailed analysis of movement velocity profile which has gained acceptance in the corresponding field of research (Hermsdörfer et al., 1996).

Furthermore, there are extreme outliers for the take-over time with the control condition concept in situation B, none with the symmetrically transforming one. In case there is no extrinsic motivation for drivers to take over, some participants seem not to understand the need to take over solely based on the warning signals. The keep interacting with the non-driving related task, unaware of the requirement to take over control. This issue disappears with the transforming steering wheel; it obviously helps drivers to understand the take-over request and to act accordingly.

In conclusion, the results of this experiment indicate that the influence of the steering wheel concept on the take-over process depends on the actual technical concept of transformation. With the symmetrical solution, the main effects are rather positive as they show shorter reaction times shortly after the TOR. Based on these results it may be stated that the transformation principle has the potential to resolve the competing design goals of automated and manual driving, even with positive effects for the transition task. These advantages potentially increase as drivers get used to the transformation concept over time; participants of the reported experiment were completely new to it. Still, it is suggested that the concept should be refined further and simple mechanical solutions need to be found to tap the full potential of steering wheel transformation.

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References

Endsley, M.R., & Kiris, O. (1995). The out-of-the-loop performance problem and level of control in automation. *Human Factors, 37,* 381-394.

Gold, C., Damböck, D., Lorenz, L., & Bengler, K. (2013). “Take over!” How long does it take to get the driver back into the loop?. In *proceedings of the Human Factors and Ergonomics Society Annual Meeting* (pp. 1938-1942). USA: SAGE Publications.

Hermsdörfer, J., Mai, N., Spatt, J., Marquardt, C., Veltkamp, R., & Goldenberg, G. (1996). Kinematic analysis of movement initiation in apraxia. *Brain, 119,* 1575–1586.

Kerschbaum, P., Lorenz, L., & Bengler, K. (2015). A transforming steering wheel for highly automated cars. In *proceedings of the 2015 IEEE Intelligent Vehicles Symposium* (pp. 1287-1292). USA, IEEE Xplore.

Lorenz, L., Kerschbaum, P., & Schumann, J. (2014). Designing take over scenarios for automated driving How does augmented reality support the driver to get back into the loop?. In *proceedings of the Human Factors and Ergonomics Society Annual Meeting* (pp. 1681-1685). USA: SAGE Publications.

Merat, N., Jamson, A.H., Lai, F.C., Daly, M., & Carsten, O.M. (2014). Transition to manual: Driver behaviour when resuming control from a highly automated vehicle. *Transportation Research Part F*, *27*, 274-282.

Naujoks, F., Mai, C., & Neukum, A. (2014). The effect of urgency of take-over requests during highly automated driving under distraction conditions. In *proceedings of the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014* (pp. 2099-2106).

Society of Automotive Engineers (2014). *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems* (Standard J3016_201401). USA: SAE Society of Automotive Engineers.

Yantis, S. & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *10,* 601–621.