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Expanding Haptic Shared Control with Tactile Stimuli

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Einmal Löwe, immer Löwe.

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Kurzfassung

Fahrerassistenzsysteme (FAS) helfen Fahrenden dabei die Fahraufgabe sicher auszuführen. Bei Fahrten mit dem FAS Haptic Shared Control (HSC) bringen Fahrende und ein System gleichzeitig Drehmoment auf das Lenkrad eines Fahrzeugs auf. Sie lenken das Fahrzeug gleichzeitig und Fahrende wissen jederzeit, wohin das System fahren möchte. HSC berechnet eine aus technischer Sicht ideale Trajektorie, der das Fahrzeug folgen sollte, und regelt das Drehmoment, dass das System am Lenkrad aufbringt, entsprechend der Abweichung von der idealen Trajektorie. Das Drehmoment muss aus Gründen der Sicherheit und Kontrollierbarkeit limitiert werden, in dieser Dissertation bspw. auf 1,5 Nm. Damit ist die direkte Abhängigkeit von Abweichung und Drehmoment nur noch bis zum Limit von 1,5 Nm gegeben. Alle Drehmomente, die durch größere Abweichungen errechnet werden, also > 1,5 Nm, reduzieren sich auf das Limit von 1,5 Nm. Damit gehen Fahrenden Informationen über die Höhe der Abweichung von der Trajektorie verloren, da verschiedene Abweichungen nur noch das identische Drehmoment in Höhe des festgelegten Limits von 1,5 Nm hervorrufen. Diese Dissertation evaluiert, ob dieser abgeschnittene Teil des Drehmoments und die damit verbundenen Informationen zur Abweichung von einer Trajektorie ersetzt werden können, wenn die assistierenden Informationen über den taktilen Kanal statt per Drehmoment übermittelt werden.

Dazu behandelt diese Dissertation die Entwicklung und Evaluation einer taktilen Vorrichtung „Tactile Wave Generator" (TWG). TWG ist ein Lenkrad-Prototyp mit 48 im Lenkradkranz verbauten Hubmagneten. Die Hubmagneten sind radial angeordnet und drücken ihren Pin in die Haut eines Fahrenden wenn dieser das Lenkrad hält. TWG kann dynamische Muster mit Druckpunkten auf der Haut erzeugen, wenn die ausgewählten Hubmagneten und die zeitliche Abfolge der Aktivierungen variiert werden. Diese Muster liefern Fahrenden Informationen, in welche Richtung und mit welcher Stärke gelenkt werden soll. Dies entspricht den Informationen, die bei HSC das Drehmoment übermittelt.

Diese Dissertation beschreibt die iterative Entwicklung, Konstruktion und Evaluation des TWG Prototypen. Dies beinhaltet Parameter der grundlegenden menschlichen taktilen Wahrnehmung sowie Probanden Feedback aus drei Fahrsimulatorstudien. Untersucht wurden unter anderem verschiedene Muster von Druckpunkten, verschiedene Leistungen und damit Kräfte, mit denen die Hubmagneten Druck auf die Haut ausüben sowie verschiedene zeitliche Abstände zwischen Aktivierungen verschiedener Hubmagneten. Die Ergebnisse zeigen, dass dynamische Muster besser als statische erkannt werden, dass mehr Leistung zu besserer Wahrnehmung führt und dass die Geschwindigkeit der Muster, also die zeitlichen Abstände zwischen verschiedenen Aktivierungen, individuell eingestellt werden muss.

Die Erkenntnisse zur Gestaltung der Muster hinsichtlich Dynamik, Leistung und Geschwindigkeiten wurden in einem finalen Prototyp umgesetzt. In einem Fahrsimulator wurde TWG in einem Vergleich mit Fahrten mit Assistenz durch HSC evaluiert. Die Ergebnisse der finalen Probandenstudie zeigen, dass TWG Probanden nicht hilft, signifikant öfter eine richtige Trajektorie zu wählen, wenn TWG und HSC gleichzeitig genutzt werden. Dabei sind die Informationen von TWG nicht in der Lage, das über dem Sicherheitslimit abgeschnittene Drehmoment von HSC ausreichend zu ersetzen. Verschiedene Aktivierungsgeschwindigkeiten von TWG waren dennoch in der Lage, Probanden auf signifikant unterschiedliche Trajektorien zu lenken, wenn keinerlei Drehmoment von HSC aufgebracht wurde. Dies zeigt sich sowohl anhand signifikant unterschiedlicher Fahrzeugpositionen am Ende der TWG Assistenz als auch bei Änderungen der Orientierung des Fahrzeugs je nach Aktivierungsgeschwindigkeit. Generell sind taktile Muster geeigneter für kontinuierliche Anwendungen, wie bspw. Spurhalte-Assistenz, da sie stets einen minimalen Zeitraum zur Durchführung benötigen, der in kritischen Szenarien nicht garantiert werden kann. Diese Arbeit hebt zudem Herausforderungen bei der Konstruktion von physischen Prototypen für taktile Stimulation hervor.

Zusammenfassend lässt sich festhalten, dass taktile Stimulation das Potential besitzt, das Lenkverhalten von Fahrenden zu verändern. Aktives Drehmoment bleibt jedoch der dominierende Faktor, der die Wahl einer Trajektorie beeinflusst.

Abstract

Driver assistance systems (DAS) help drivers to safely master the driving task. When driving with the DAS Haptic Shared Control (HSC) a system and the driver apply torque to steering wheel of vehicle at the same time. They steer the vehicle simultaneously and the driver is always aware where the system wants to go. HSC calculates an ideal trajectory the vehicle should follow. It controls the applied torque based on the deviation from the trajectory. The systems torque has to be limited for safety and controllability, e.g. at 1.5 Nm in this thesis. This way the torque is only dependent on the deviation up to the torque limit of 1.5 Nm. All torques that follow from larger deviations, i.e. > 1.5 Nm, are reduced to the limit of 1.5 Nm. Drivers lose important information about the amount of deviation from the trajectory as a consequence because different deviations all result in the identical torque in the amount of the torque limit. This thesis evaluates if the cut off part of the torque and the connected information about deviations can be replaced by transmitting information using the tactile information channel instead of torque.

This thesis presents the development of a tactile device called "Tactile Wave Generator" (TWG). TWG is a steering wheel prototype that has 48 solenoids embedded in its rim. The solenoids are oriented radially and push their pin into the skin of a drivers hand when holding the steering wheel. TWG can create dynamic patterns of pressure points on the skin when the chosen solenoids and the timing of the activations are variated. These patterns are used to provide information to drivers about direction and magnitude of required steering. This equals the information torque provides during HSC.

This thesis describes the iterative development, construction and evaluation of the TWG prototype. It includes parameters from basic human tactile perception as well as user feedback from three driving simulator studies. Properties investigated include different patterns of pressure points on the skin, different powers and with it the force with which solenoids press into the skin and different activation speeds which are created by varying the delay between activations of different solenoids. Results indicate that dynamic patterns are better recognized than static ones, that more power equals better perception of separate pressure points and that activation speeds, i.e. the delays between two separate activations, have to be adjusted individually.

The results on pattern design considering dynamics, power and speeds were used to built a final prototype. This device was evaluated in comparison to driving with HSC in a driving simulator. Results of the final user study indicate that TWG does not improve participants ability to choose a correct trajectory when steering with HSC and TWG. Information from TWG is not able to replace the information that gets lost by capping HSCs torque. Different speed configurations of TWG were still able to lead participants on significantly different trajectories when no torque from HSC was applied. This is expressed both in covered distance as well as change in orientation of the vehicle. Tactile patterns are generally more suited for continuous support like lane keeping rather than single event assistance because they require a certain minimal time to be executed which can't always be guaranteed in critical scenarios. This work also highlights pitfalls when constructing physical prototypes for tactile stimulation.

This thesis concludes that tactile stimulation has the potential to influence drivers steering behavior yet active steering torque remains the major factor influencing a driven trajectory.

Contents

1. Introduction and Goal

Haptic Shared Control (HSC) is an interaction concept for the driving task in vehicles. In this context *control* means an assistance system actively influences where the vehicle is moving. *Shared* means it interactively moves the vehicle at the same time as the driver. Both are equal partners in a cooperation. *Haptic* means the assistance system and the driver use forces and torques to execute their control. HSCs is available for both longitudinal and lateral vehicle control. Lateral control has seen far more research and is also at the center of this thesis. HSCs goal is improved steering performance which can help to avoid accidents. HSC uses input from technical sensors to calculate an ideal trajectory for a vehicle, considering aspects like safety, comfort and individual driver preferences. It then continuously applies torque to the steering wheel of the vehicle to steer and actively influence the trajectory of the vehicle to a certain extent. It can not fully replace a driver and steer the vehicle entirely by itself. While HSC applies torque, drivers use the steering wheel and steer the vehicle as usual at the same time. Drivers can sense the applied torque with their hands on the steering wheel and adjust their own steering action according to direction and magnitude of HSCs torque. (Abbink, Mulder, & Boer, 2012)

HSC also has limitations. Torque can have a dangerous impact if it surpasses limits that drivers physically can not control anymore. Too much torque can also overpower a driver that wants to overrule the system. That is why torque is usually limited or saturated when using HSC. A saturated torque limits HSCs ability to influence the trajectory of a vehicle. In addition, the driver can no longer distinguish between different trajectories HSC might have calculated because different torques above the safety limit for different trajectories are saturated at the same value (fig. 1.1). With HSCs active input being limited it is even more important to utilize the driver to provide the remaining needed steering input to reach an optimal trajectory. One approach is to provide the driver with the information to distinguish trajectories, that gets lost by capping the torque, using other sensory systems than haptic.

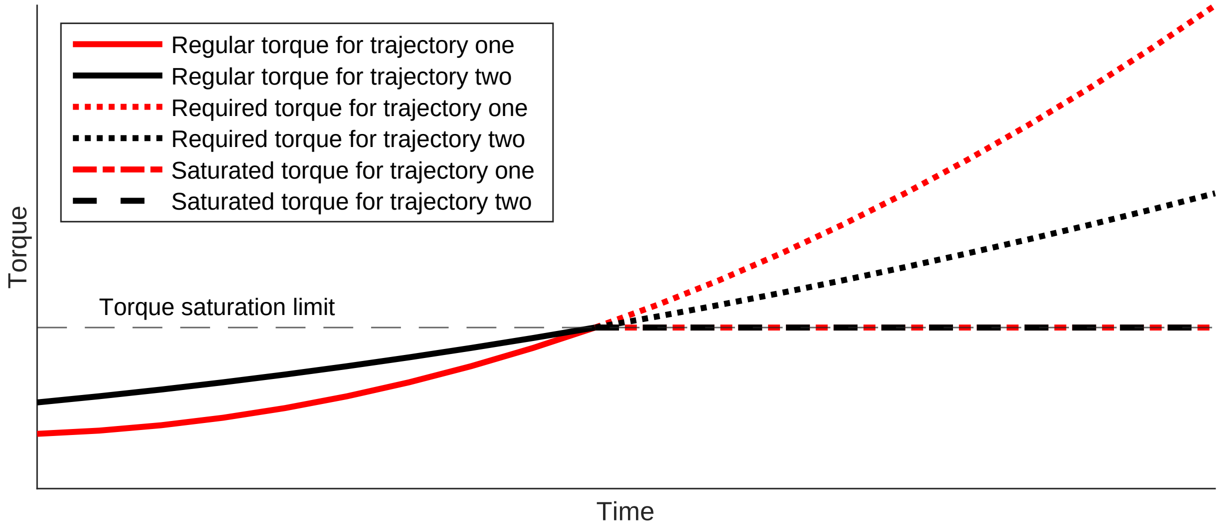


Figure 1.1: *Illustration of assistance torques for two different trajectories: Both torques are applied with their regular amount while they are below the safety limit. They are saturated at the same limit when their required values exceed the limit. Torques for different trajectories can not be distinguished while saturated.*

There are established channels to transmit information to a driver in the interior vehicle context. While many driver assistance systems utilize the visual and acoustic channel, this thesis leans on HSCs original description: *haptic*. This umbrella term incorporates four different sensory systems:

- *Proprioceptive*, which uses muscles, tendons and joints to sense forces and torques,
- *nociceptive*, which registers pain,
- *thermosensitive*, which senses temperatures and temperature changes and
- *tactile*, which perceives changes applied to the skin. (Blattner, 2014)

All haptic sensory systems can potentially fulfill the task of transmitting the lost information during HSC to the driver. Yet applications to create fitting stimuli require different resources which means that not all stimulations are equally easy to produce in the context of this thesis. This work focuses on *tactile* stimulation because it is the most feasible when it comes to resource management.

The goal of this thesis is to evaluate if *tactile* stimulation can be used to compensate the information lost by capping HSCs torque. This becomes especially relevant in scenarios where different torques above the limit could lead to different trajectories but information to distinguish trajectories is lost due to saturation of the torque. Successful compensation would lead to significantly more choices of a correct trajectory with HSC combined with tactile assistance compared to scenarios where solely HSC with a limited torque is available.

This thesis is structured as follows: Chapter 2.1 explores what *haptic* actually means and clarifies that HSC uses *proprioceptive* stimulation. *Tactile* stimulation uses different receptors, as explained in chapter 2.2. Chapter 2.3 gives an overview of HSC and its configurations, applications and limitations. Chapter 3 documents the initial construction and iterative improvement of a tactile device called "Tactile Wave Generator" (TWG). TWG is a steering wheel that has 48 solenoids embedded in its rim. The solenoids can extend their pins and indent the skin on the drivers hand at different locations and at different times. This can be used to create dynamic patterns on drivers skins. The device is then evaluated in chapter 4.1. Chapter 4.2 describes a driving simulator study in which TWG was used in addition to HSC. The intention was for TWG to substitute the information missing from HSCs capped torque as previously explained. Chapter 5 sums up the work performed in this thesis and draws conclusions about the overall contribution to the problem described before as well as identified potential for improvement and continued research with TWG.

2. Current State of Haptic Research

2.1. Terminology

The term *haptic* is not uniformly defined. It is most commonly connected to the sense of touch, but more detailed definitions differ depending on the research area. Spence and Ho (2008) for example distinguish between interface design and psychophysics. They report a difference for the latter between the terms *haptic* and *tactile*. Here, *haptic* refers to stimuli that come from active contact between the human body and a physical object of interest – initiated by the human. *Tactile* on the other hand refers to passive contact initiated by the physical object. Spence and Ho (2008) also point out an exemption from this view for "active torque feedback delivered by certain steering wheel signals": This specific use case, which matches the defintion of haptic shared control (see chapter 2.3), is also referred to as *haptic*.

Blattner (2014) on the other hand offers a classification of these terms that relies on human physiology (Fig. 2.1). *Haptic* is an umbrella term for four different forms of perception that are divided by their physiological receptors, i.e. mechanosensors, proprioceptors, thermal receptors and nociceptors. *Tactile* is one of those options and now a part of haptic instead of an alternative for it.

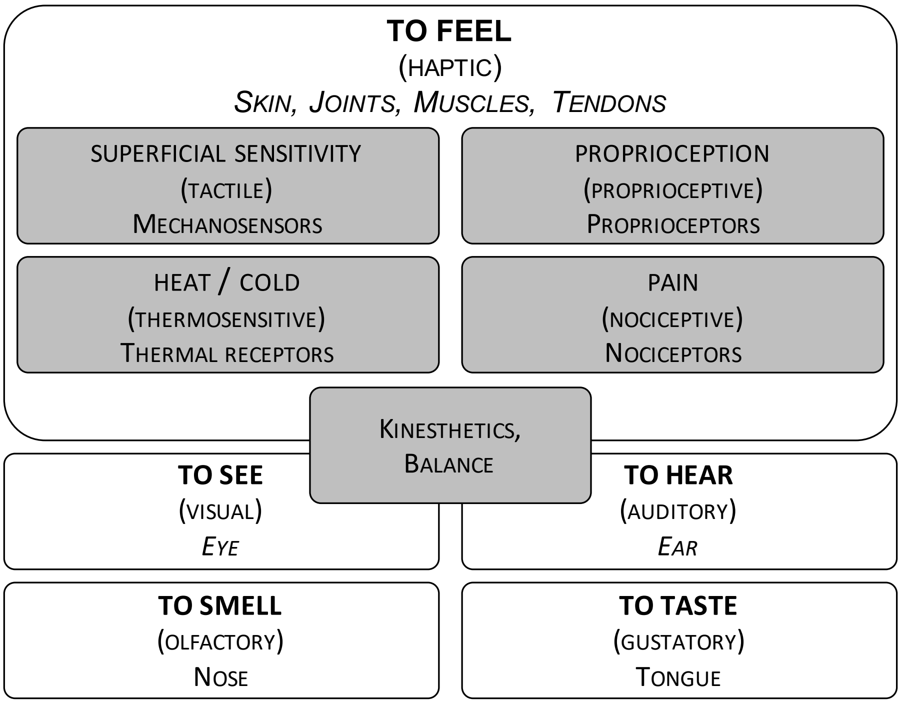


Figure 2.1: *Division of human sensory systems (Fig. taken from Blattner (2014, p. 19), with content from Reisinger and Wild (2008); T. A. Kern, Matysek, and Sindlinger (2009), translated by the author)*

The classification in fig. 2.1 also fits better with other research, i.e. studies with manipulation of the skin by pressure (Geldard & Sherrick, 1972; Boldt, Gogulski, Gúzman-Lopéz, Carlson, & Pertovaara, 2014), which is considered *tactile*, and investigations of known *tactile* phenomena in *thermoceptive* and *nociceptive* stimulation (Trojan et al., 2006), which shows that these perceptions are also treated as separate in the literature. *Haptic* or *tactile* is also often automatically equated to *vibrotactile* (i.e. Xin et al. (2021)). Vibration is a process of iteratively applying small amounts of pressure at the same position and releasing it again in a short period of time. It is perceived by one of four different receptors in the skin (see chapter 2.2). This qualifies the sensation as *tactile* following the definition from Blattner (2014), but forbids a synonymous use with the terms *haptic* or *tactile*. The remainder of this thesis follows the definition by Blattner (2014).

2.2. Basics of Tactile Perception

Table 2.1 gives an overview of the four different mechanoreceptors in the human skin for tactile perception. *Pacinian Corpuscles* exist in glabrous and hairy skin. They are stimulated by vibration, acceleration and can sense roughness. They are activated by skin motion. *Ruffini Endings* are also found in glabrous and hairy skin. They can sense skin stretches as well as lateral and static forces. They also detect a motions direction. Ruffini Endings are stimulated by skin motion and sustained skin deformation. *Meissner Corpuscles* only exist in glabrous skin and detect velocity, flutter and slip. They are also responsible for grip control. Like the other mechanoreceptors, they are stimulated by skin motion. The fourth type are *Merkel Disks*. These mechanoreceptors only exist in glabrous skin like the inside of a hand, and are therefore most important for this thesis. They can detect skin curvature, pressure and different forms, textures and edges. They are stimulated by skin motion and sustained skin deformation. (Hale & Stanney, 2004)

Merkel Disks, Ruffini Endings and Meissner Corpuscles are also referred to as *Slowly Adapting 1 (SA1)*, *Slowly Adapting 2 (SA2)* and *Rapidly Adapting (RA)*. These characterizations stem from the receptors reactions to stimulations. Fig. 2.2 shows when these mechanoreceptors send out signals depending on a pressure sensation with the magnitude S. Pacini Corpuscles only signal for accelerations at the on- and offset of the change in stimulus. RA react throughout the change in skin impression. SA1 and SA1 add more signals during the static phase of the skin impression. Mathematically, SA1 responds not only to the presence of pressure but also to the change in pressure like RA. (Handwerker, 2006)

SA1 mechanoreceptors respond to stimuli in a range of $0.4 \ - \ 10 \ Hz$, meaning less than one activation per second is already fitting for this type of receptor (Hale & Stanney, 2004). Pressure is registered by mechanoreceptors starting in a range of $0.06 \ - 0.2 \ N/cm^2$ (Hale & Stanney, 2004; Sherrick & Cholewiak, 1986). Treede (2011) states the two-point threshold, the distance at which two spatially separate stimulations can be distinguished, for SA1 mechanoreceptors at approx. $10 \ mm$ on the glabrous side of the hand. This value decreases moving towards the fingertips and increases moving towards the wrist. The SA1 mechanoreceptors offer the best properties for sufficient and efficient stimulation in the use case of this thesis.

Table 2.1: *Haptic tactile skin mechanoreceptor characteristics. (Excerpt from Hale and Stanney (2004))*

	Mechanoreceptors			
	Pacinian Corpuscles	Ruffini Endings	Meissner Corpuscles	Merkel Disks
	Pacini	Slowly Adapting	Rapidly Adapting	Slowly Adapting
Haptic Features	PC	SA2	RA	SA1
Skin Type	Glabrous and hairy	Glabrous and hairy	Glabrous	Glabrous
Stimulation Objective (physical parameters to be sensed)	Vibration, acceleration, roughness	Skin stretch, lateral force, motion direction, static force	Velocity, flutter, slip, grip control	Skin curvature, pressure, form, texture, edges
Stimulation Type	Skin motion	Skin motion and sustained skin deformation	Skin motion	Skin motion and sustained skin deformation
Spatial resolution	Very poor ($2\ cm$)	Poor ($1\ cm$)	Fair ($3 - 5\ mm$)	Good ($0.5mm$)

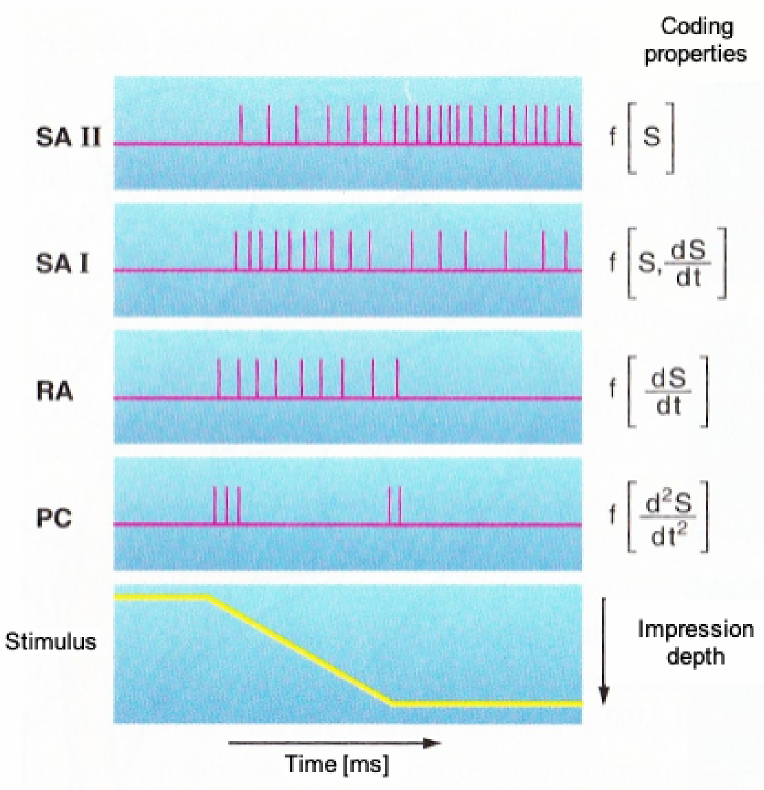


Figure 2.2: *Comparison of the temporal reaction of the different sensor types to a pressure stimulus with the magnitude S. (Fig. and caption [translated by the author] from Handwerker (2006))*

2.3. Haptic Shared Control

Haptic Shared Control (HSC) was rudimentarily introduced as an applied concept for driver assistance in 2005 by Griffiths and Gillespie (2005). Abbink and Mulder (2010) describe it as an intermediate form of driver assistance on the way to full driving automation, because neither the human driver nor a technical system take over the entire driving task on their own (Abbink & Mulder, 2010). The driving task can be divided into longitudinal and lateral control. HSC can be applied for both, but this thesis focuses only on the lateral aspect of the driving task, instead of solutions like the exemplary haptic gas pedal, i.e. Abbink (2006), for longitudinal assistance.

With HSC, input from the driver and the system is applied to the drive train in parallel. Fig. 2.3 shows a schematic of haptic shared control. For lateral control, the assistance system is linked to the steering wheel by connecting an electrical engine to the steering column. The control interface H_{ci} in fig. 2.3 is the steering wheel.

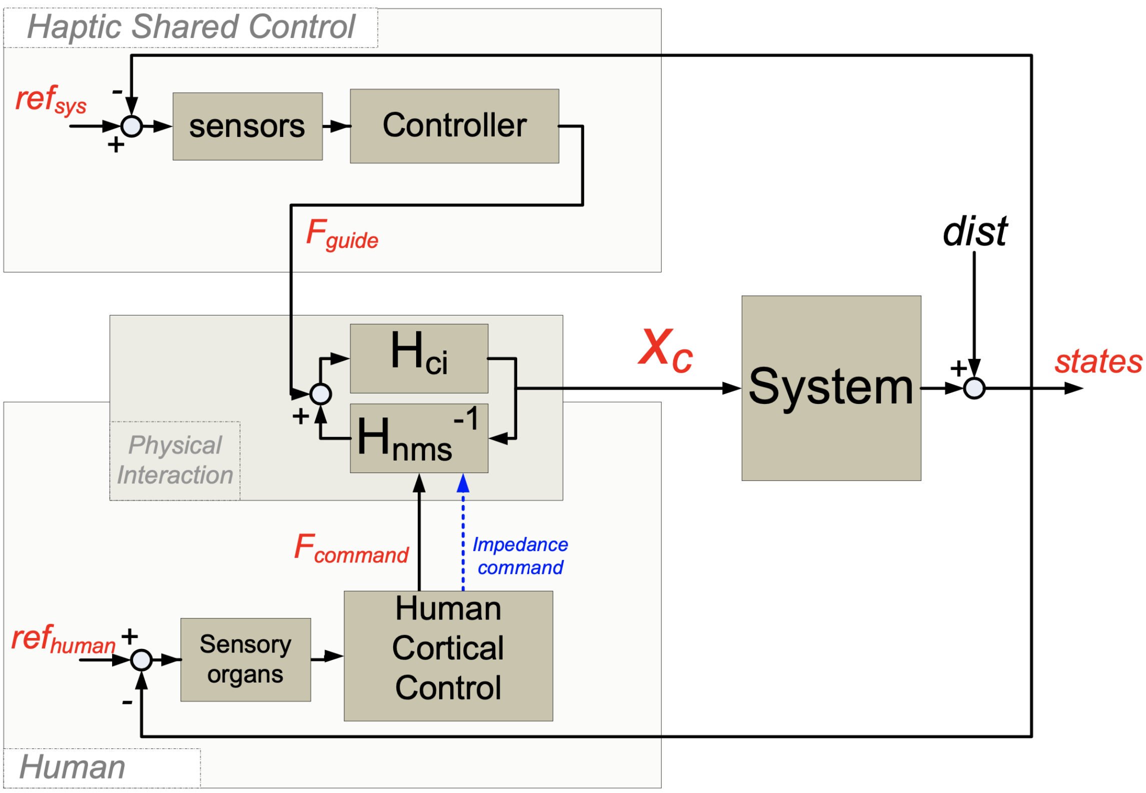


Figure 2.3: *A schematic, symmetric representation of [...] haptic shared control. [...] The human and system have sensors to perceive changes in system states (possibly perturbed by dist), each having a goal (ref_{human} and ref_{sys}, respectively). During haptic shared control, both human and system can act with forces on the control interface (with $F_{command}$ and F_{guide} respectively). Through physical interaction, the control interface (H_{ci}) exchanges force and position with the human limb (H_{nms}) [...]. (Fig. and caption from Abbink and Mulder (2010))*

HSC provides several advantages compared with manual driving. With HSC, "the driver is not only aware of the system's actions, but can also choose to influence and overrule the systems activity" (Abbink & Mulder, 2010, p. 501). Abbink et al. (2012, p. 19) sum up several different studies on HSC with the results indicating "faster and more accurate vehicle control, lower levels of control effort" and "reduced demand for visual attention".

The authors in de Winter and Dodou (2011) point to several disadvantages that HSC itself and many of its studies have. They critically reflect that almost all studies use perfect systems which is not an accurate representation of how systems behave in the real world. The authors also classify their investigated studies as suitable only for standard but not emergency steering scenarios. Finally, de Winter and Dodou (2011) argue that drivers potentially get confused with the division of responsibility and influence on the driving task.

Aside from performance advantages and disadvantages for HSC, there is another issue that some studies address. In theory, an electric engine can apply much more torque than a driver ever could. Yet the driver is supposed to always remain in charge (Abbink et al., 2012), also known as controllability of a system (EN ISO 17287, 2003). Della Penna, van Paassen, Abbink, Mulder, and Mulder (2010) also showed positive effects of limiting their shared control system. Different studies on steering systems in general report different controllable torques. Itoh, Inagaki, and Tanaka (2012) used $3\ Nm$ and report frustration for drivers who wanted to steer in the other direction. Neukum, Paulig, Frömmig, and Henze (2010) report torques of $4\ Nm$ to not be controllable anymore. Schneider, Purucker, and Neukum (2015) see $4\ Nm$ as acceptable but not $6\ Nm$. Keller et al. (2011) approve up to $5\ Nm$ while Hesse and Schieben (2013) use up to $9.9\ Nm$. Köhler et al. (2013) and Neukum, Ufer, Paulig, and Krüger (2008) use different measures as limits: $700\ °/s$ rotation speed of the steering wheel (Köhler et al., 2013) and a yaw rate of $4.0\ °/s$ at $50\ km/h$, $3.0\ °/s$ at $100\ km/h$ and $2.5\ °/s$ at $150\ km/h$ (Neukum et al., 2008). The precise maximum value for torque depends on the individual setting and use case. Yet these studies show that steering systems should be limited to stay controllable in accordance with EN ISO 17287 (2003).

HSC research so far has neglected emergency steering scenarios or more generally speaking scenarios where a potential torque limit became a problematic factor. There also is no standardized torque limit for safety or controllability. This means the feasibility of HSC systems for higher torques remains an open question. Kalb and Bengler (2018) summarize several studies and show systematically what other scenarios still require research when the entire steering cooperation relies on torque.

2.4. Tactile Steering Wheels

Tactile devices have been used in combination with steering tasks before. Useful locations of devices are among topics often investigated (for a more extensive review see Petermeijer, de Winter, and Bengler (2016)) yet this work only focuses on tactile stimulation that is directly embedded into the steering wheel. This allows for a close stimulus-response capability (D. Kern, Marshall, Hornecker, Rogers, & Schmidt, 2009) which puts the source of information spatially close to the location where the driver should react to the stimulation. All tactile devices presented in this chapter incite the driver to steer the vehicle in some way, so it is useful to initiate the stimulation at the same control element.

Vibration, also known as vibrotactile, is used most compared to the other haptic channels shown in fig. 2.1 when tactile devices are built (e.g., Petermeijer et al. (2016), Xin et al. (2021)). D. Kern et al. (2009) were among the first to extend the concept of binary vibration (yes or no) into more complex patterns in the context of steering wheels. The authors build a steering wheel prototype that had six separate vibration motors evenly spaced out around the rim (Fig. 2.4). They controlled the intensity, the location and duration of individual vibrations to enhance perception of navigational information. The system could produce static and dynamic patterns. D. Kern et al. (2009) report two flaws of their physical build: Drivers could simply miss vibrations by placing their hand too far away from the six vibration locations. The authors compensated this by setting all vibrations to maximum intensity. This provoked the second problem where vibrations resonated to other parts of the steering wheel. That made it harder for subjects to correctly identify the location and timing of vibrations. The authors also mention the inconvenience that their prototype had a filled out center due to the built-in electronics. Finally, they report two more interesting configurations: according to D. Kern et al. (2009) the minimum activation period was 300 ms because shorter activations were not noticeable. They also ran each pattern or activation twice as subjects preferred this to confirm their initial judgement from the first activation. (D. Kern et al., 2009)

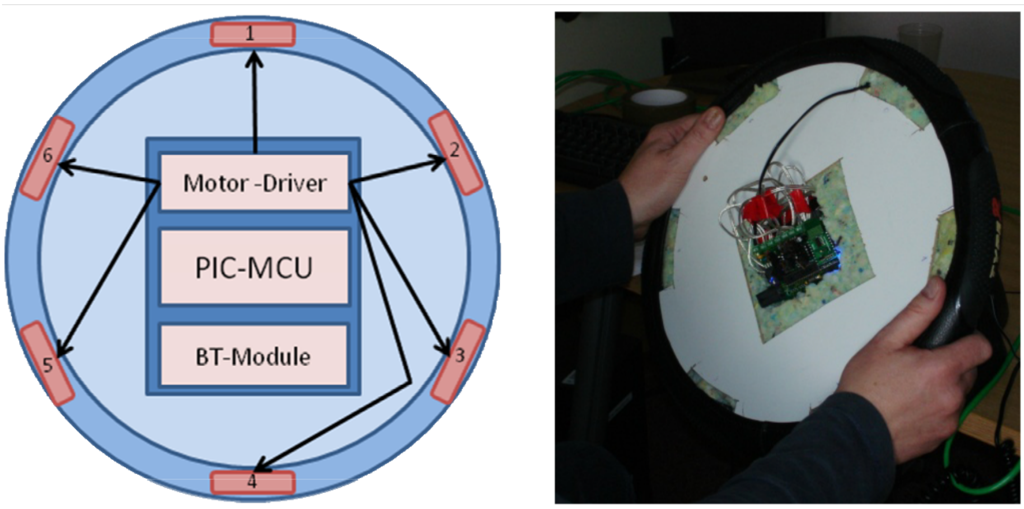
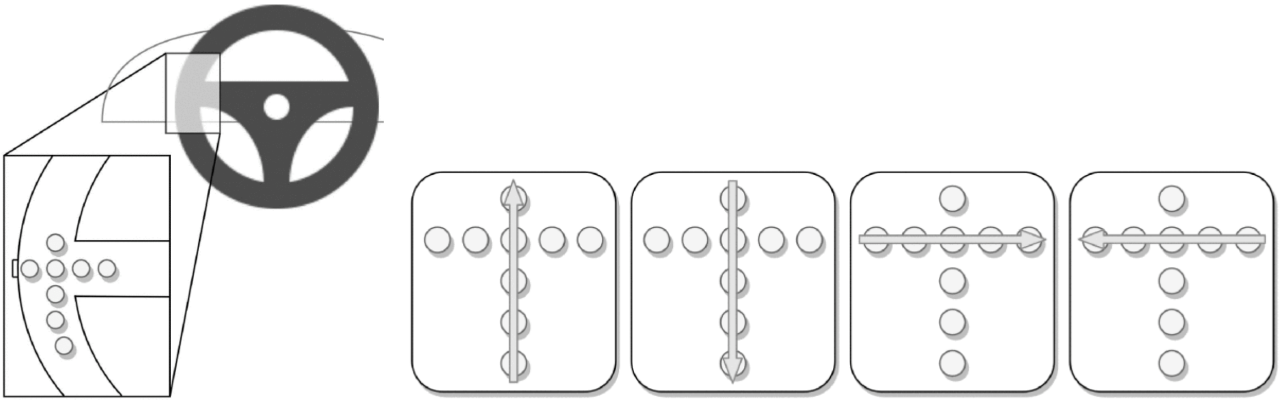


Figure 2.4: *The steering wheel [from D. Kern et al. (2009)]: concept and internal data flow and photo of the prototype used in the study with the elements exposed. (Fig. and caption from D. Kern et al. (2009))*

Quintal and Lima (2022) also implemented a device in their "HapWheel" that they classify as haptic. It consists of nine vibration motors that are aligned in the form of a cross on the left side of a steering wheel (Fig. 2.5a & 2.5b). The authors used this array to display four different patterns by activating the individual motors in sequence. Each pattern lasted 350 ms. The patterns provided feedback for interactions with an in-vehicle information system. (Quintal & Lima, 2022)

Hwang and Ryu (2010) expand the concept from D. Kern et al. (2009) and use 32 instead of just six vibration motors spread out around the steering wheel rim (Fig. 2.6). The authors use this array to implement patterns where actuators are activated one after another, starting at the top and going down one side to the bottom of the steering wheel. They also tested a pattern where activations of actuators overlapped time wise. Yet only the patterns where one actuator at a time was active used the perception aspect called "sensory saltation" (also known as "cutaneous rabbit" (Geldard & Sherrick, 1972)) (Hwang & Ryu, 2010).



(a) Actuators position in the steering wheel. (Fig. cropped and part of the caption from Quintal and Lima (2022))

(b) *Activation sequence followed by the actuators to portray the swipe up, down, right, and left patterns. (Fig. and caption from Quintal and Lima (2022))*

Figure 2.5: *Setup of the components used in the users study with "HapWheel".*

This phenomenon, which is similar to the phi phenomenon in visuals, implies that humans feel a third imaginary stimulation between two spatially different stimuli that are applied in short sequence. That extra stimulation increases the impression of a wave of of stimuli running down the side of the steering wheel. This wave represents the rotation direction that the driver should apply to the steering wheel. Hwang and Ryu (2010) convey directional information to the driver this way. The authors used inter-stimulus onset intervals (ISO) of $30\ ms$ which is the time between individual activations. This time is based on results from Hill and Bliss (1968) that say humans require at least $26\ ms$ between stimuli to discriminate separate stimulation locations. (Hwang & Ryu, 2010)

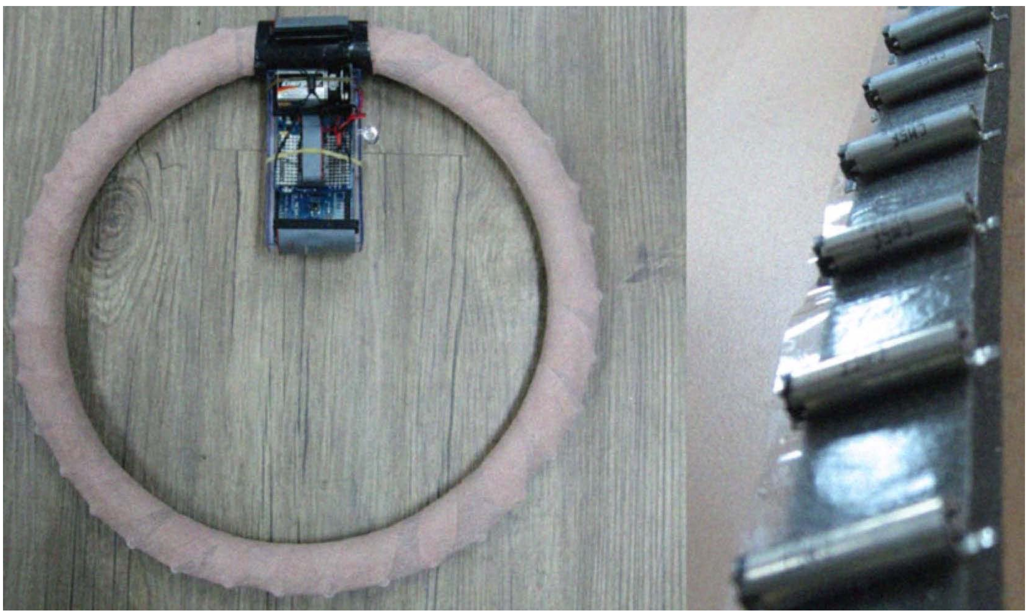


Figure 2.6: *32 vibration motors spread out across the steering wheel used by Hwang and Ryu (2010) (Fig. taken from Hwang and Ryu (2010)*

Kim, Hong, Li, Forlizzi, and Dey (2012) expand on the idea from Hwang and Ryu (2010) and use 20 vibration motors around the steering wheel rim. The difference is a foam embedding for all motors to avoid resonance of vibration to other parts of the steering wheel (Fig. 2.7). The authors do not report on the success or potential implications of their foam embedded approach. (Kim et al., 2012)

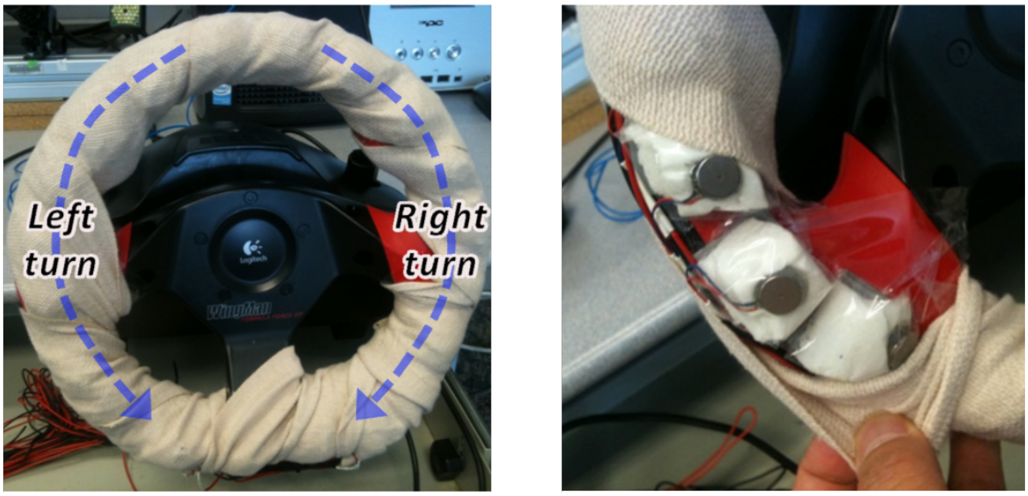


Figure 2.7: *20 vibration motors embedded in foam spread out across the steering wheel used by Kim et al. (2012) (Fig. taken from Kim et al. (2012)*

An entirely different approach to tactile stimulation comes from Borojeni, Wallbaum, Heuten, and Boll (2017). They built a steering wheel prototype with movable rim parts at the 3 o'clock and the 9 o'clock position (Fig. 2.8). The two movable wooden parts are controlled by a central motor connected by strings. The two movable plates press in the hands of a driver in the systems desired steering direction. The authors used their systems for take-over requests (TOR) during level 3 automated driving. They report no significant performance increase with their system, mostly because the tested scenarios started without drivers hands on the steering wheel. The system could only be activated once drivers put their hands on the steering wheel. At that point too much time had passed for a successful transition of the driving task. The authors also report a lack of force of their prototype which made it harder for subjects to correctly perceive the direction cue. (Borojeni et al., 2017)

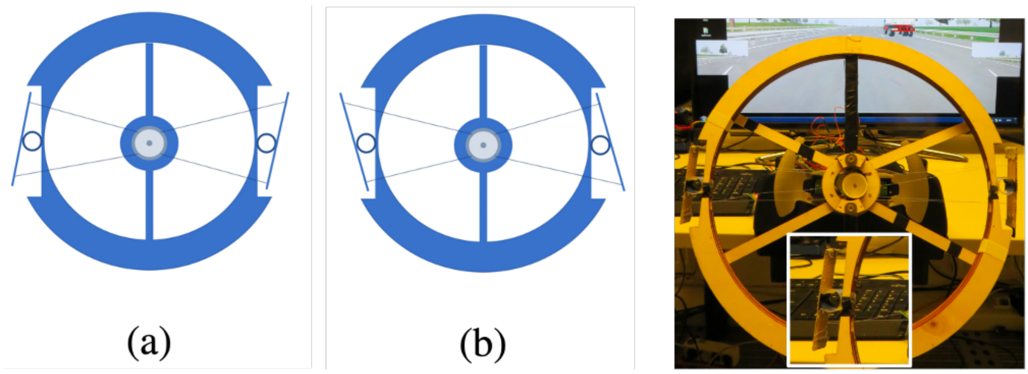


Figure 2.8: *Schematics of the steering wheel prototype from Borojeni et al. (2017) with a) directional information to the left, b) directional information to the right and an image of the real prototype. (Fig. taken from Borojeni et al. (2017)*

Enriquez, Afonin, Yager, and Maclean (2001) offer yet another novel approach. They build the steering wheel rim as an inflatable plastic tube (Fig. 2.9). This tube could expand its diameter if it was filled with pressured air. Inflating and deflating the tube increased and decreased pressure on the drivers hand. The authors also report that repeating activations helped their subjects to confirm their initial judgement from the first activation, similar to D. Kern et al. (2009). Enriquez et al. (2001) used their device only as a warning device independent from the steering task. Yet it is another example for tactile stimulation that does not require vibration. (Enriquez et al., 2001)

Figure 2.9: *Haptic steering wheel [used by Enriquez et al. (2001)]. Built from PVC conduit and a vinyl steering wheel cover; the pneumatic display is located beneath the steering wheel cover, under the subject's right hand. (Fig. and caption taken from Enriquez et al. (2001))*

Medeiros-Ward, Cooper, Doxon, Strayer, and Provancher (2010) do not work with perpendicular skin indentation but with parallel skin shearing. The authors built a steering wheel prototype that had a special conical hole for the drivers finger tip. A small rubber moving part at the bottom of the conical hole pushed or pulled the finger tips skin forward or backwards, creating a stimulation for the driver (Fig. 2.10). Two such devices were mounted on a steering wheel (Fig. 2.11). The direction of displacement was tangential to the steering wheel rim. The absolute directions of both skin movements were not equal. They individually moved in the direction that would indicate a clockwise or counter-clockwise rotation, a concept also described by Hwang and Ryu (2010) and Kim et al. (2012). The authors also acknowledge that multiple copies of their tactile device needed to be placed everywhere on the steering wheel to allow drivers to place their hands where they wish. (Medeiros-Ward et al., 2010)

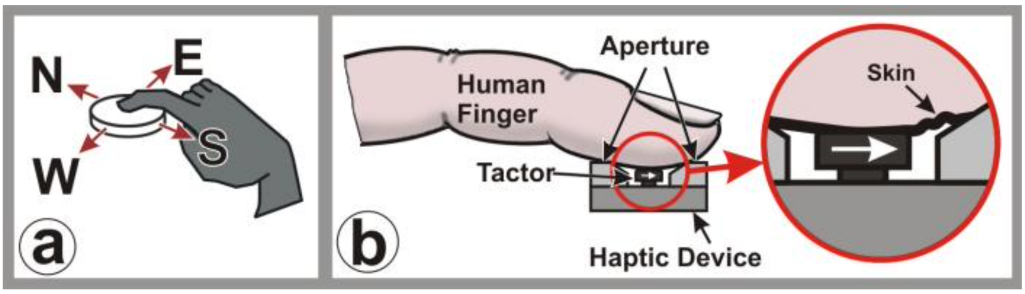


Figure 2.10: *Haptic input and direction of skin displacement (Fig. taken from Gleeson, Stewart, and Provancher (2011) as used in Medeiros-Ward et al. (2010))*

Figure 2.11: *(left) Tactile feedback devices as haptic input mounted to the driving simulator's steering wheel. The shear tactors face towards the dashboard. (right) User's hand gripping the steering wheel. The index finger is retracted to more clearly show the tactile interface. (Fig. and caption taken from Medeiros-Ward et al. (2010))*

Ploch, Bae, Ju, and Cutkosky (2016) and Ploch, Bae, Ploch, Ju, and Cutkosky (2017) also use skin shearing, but in a much larger sense. The authors build a steering wheel prototype that can rotate a layer on the side facing the driver independently from the steering wheel movement. The circular layer has a stripe of silicone on it. A small motor rotates the layer while the driver firmly holds the steering wheel. The silicone sticks to the palms skin and stretches it in one of two directions (Fig. 2.12). The device operates independent from the hands position because the silicon stripe goes all around the steering wheel.

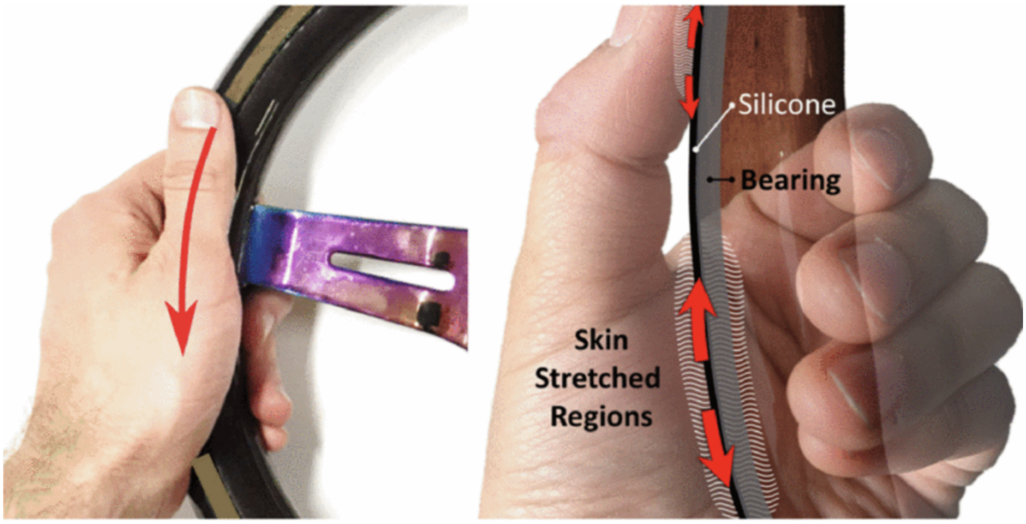


Figure 2.12: *Close-up view of the skin stretch produced by the steering wheel. (Fig. and caption taken from Ploch et al. (2016))*

Shakeri, Brewster, Williamson, and Ng (2016) are the first to use solenoids in a tactile device for steering tasks. A solenoid, also known as lifting magnet, is a device that consists of a metallic coil whose ends are connected to an electric power source. A metal pin lies in the center along the axis of the coil. Electric current is flowing through the coil when electric power is switched on. This creates an electromagnetic field in and around the coil that affects the metal pin in the middle. The pin is pushed out of the coil in one direction. The other end of the pin is usually connected to a mechanical spring. This spring is stretched when the pin is pushed out of the metal coil. The spring pulls the pin back into its original position once electrical current is turned off again. Shakeri, Brewster, et al. (2016) built six solenoids into the steering wheel rim, three at the 3 o'clock and three at the 9 o'clock position. The pins are oriented radially outwards from the steering wheel (Fig. 2.13).

The authors use different combinations of activated and non activated solenoids to create different static patterns of pressure points in drivers hands. Their results show that not more than three solenoids should be included in a pattern, otherwise recognition by subjects drops significantly. They also argue to execute a pattern only on one hand at a time which is different from the solutions with skin shearing. Overall participants can easily detect a variety of static patterns with several combinations of activated solenoids. The study included a simple lane keeping task in a simulated driving environment. Shakeri, Ng, Williamson, and Brewster (2016) expand on this principle but rotate one solenoid on each side to an orientation perpendicular to the steering wheel surface (Fig. 2.14). Perception increases compared to Shakeri, Brewster, et al. (2016) because the area below the thumb is being targeted as well. (Shakeri, Brewster, et al., 2016)

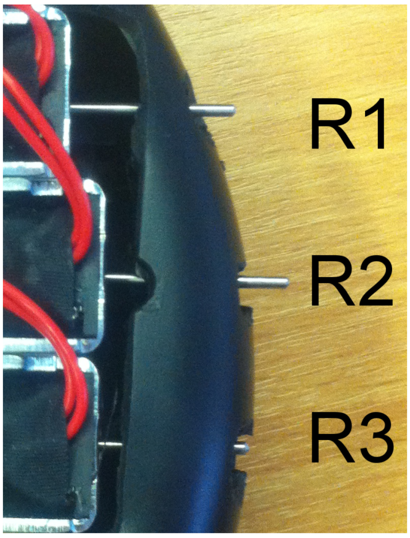


Figure 2.13: *Enlarged right side of the steering wheel [used in Shakeri, Brewster, et al. (2016)]. R1 and R2 are activated and are pushing out. R3 is not active. (Fig. and caption taken from Shakeri, Brewster, et al. (2016)*

Figure 2.14: *Close-up of the activated pins on the right side [used in Shakeri, Ng, et al. (2016)]. (Fig. and caption taken from Shakeri, Ng, et al. (2016)*

3. Development of TWG

3.1. Initial Prototype

Chapter 2.4 showed the variety of possibilities how tactile can be implemented besides using vibration. Concepts from the literature are used to develop a novel tactile device that builds on previous findings. This chapter describes the development of the first prototype of the TWG system. It was supported by a student thesis written by Titze (2018). The focus of development in Titze (2018) included the requirement to include the device as a mountable add-on for a steering wheel in a real world testing vehicles. This chapter only focuses on information and results relevant to the overall research goal of this thesis.

3.1.1. Requirements

The first step was to specify the requirements for the final system. The three top level aspects are:

a. What information the new system needs to provide: HSC has two properties: **direction** and **magnitude** of steering (depending on the deviation). The new system needs to be able to supply these information as well.

b. Where it should do so: The steering wheel is chosen as the installation space for the new system to keep both concepts in the same user space.

c. What part of haptic stimulation it should use: The stimuli will be provided using *tactile* stimulation, following the definition in chapter 2.1. *Thermoceptive* and *nociceptive* remain equally valid and interesting topics for further research but a first high level analysis showed a higher feasibility for a *tactile* prototype within the organizational boundaries of this thesis.

Titze (2018) provides a table of further requirements regarding the human user, technology and the overall system (see table 3.1).

3.1.2. Adaptions from the Literature

Chapter 2.4 shows different approaches for tactile information systems at the steering wheel. The idea was to make use of successful systems yet develop them further to generate new insight on how these concepts can be improved step by step. Limitations for TWG were set by organizational boundaries concerning technical feasibility as well as budget.

Table 3.1: *List of requirements for the construction of TWG. (Edited excerpt [translated by the author] from Titze (2018))*

Aspect	Title	Description
(A) Human user	(i) Forces	The communication device applies forces. These forces need to lie within acceptable boundaries for human users. They must not cause pain or harm at any time.
	(ii) Perceptibility	The human user has to be able to perceive the stimuli created by the communication device. The development has to consider thresholds for pressure and spatial resolution in tactile perception.
	(iii) Perception	The user must be able to perceive the information communicated by the device in distinguishable dimensions.
	(iv) Interference	The device must not interfere with the essential and conventional steering method.
	(v) Variability	The device has to be usable for the majority of drivers with regards to anthropometric qualities.
(B) Technology	(i) Stimulus generation	The device has to include technical components that are capable of producing the stimuli with regards to the dimensions direction and magnitude.
	(ii) Energy supply	The device has to be supplied with energy in the form of electric current or other operating resources. The development has to consider the functional principle of stimulus generation and a sufficient freedom for the steering wheel to rotate.
	(iii) Interface	The device needs an interface to receive signals from the simulation.
	(iv) Safety	The development needs to account for current safety standards. It needs to consider possible malfunction, sources of errors and misuse or abuse of the device. The construction has to take special care of electrical isolation to prevent electric shocks.
(C) Overall system	(i) Steadiness	The device has to sustain ordinary forces and torques that are part of a conventional steering process. It must not slip or bend.
	(ii) Material	The material has to fit the chosen functional principle as well as the intended use of the device. The choice of material has to consider the direct contact with drivers hands.
	(iii) Contact points	The device should enable as many gripping positions as possible.
	(iv) Assembly	The device has to be mountable in a way that doesn't interfere significantly with the conventional driving task.
	(v) Installation space	Physical components of the device should be as small and compact as possible.

The TWG concept extends the general idea of using solenoids to create pressure on the skin and to convey signals to a driver. Solenoids were first used by Shakeri, Brewster, et al. (2016) (Fig. 2.13). Their findings lay the basis for fulfillment of the requirements A-i, A-ii and A-iii (Tab. 3.1). Shakeri, Brewster, et al. (2016) also showed in general that pressure applied to the skin by solenoids does trigger a stimulation which is needed for the requirement B-i. D. Kern et al. (2009) first introduced the idea to place several actuators around the steering wheel rim and activate them independently to create patterns. Similar to T. A. Kern et al. (2009) the solenoids in this thesis need to have an adjustable intensity so they can differ between different magnitudes (requirement B-i). Hwang and Ryu (2010) extended this and used vibration motors in a larger number around the entire steering wheel rim (Fig. 2.6). Medeiros-Ward et al. (2010) also recommend to place tactile actuators around the steering wheel rim in large numbers to allow drivers to place their hands where they wish. TWG combines the two properties and works with a larger number of solenoids compared to Shakeri, Brewster, et al. (2016) or Kim et al. (2012). This has two advantages compared to the implementation in Shakeri, Brewster, et al. (2016): a) more combinations of activated and non activated solenoids are possible, enabling more different information to be conveyed and b) more different perception locations enable dynamic patterns, e.g. a chronological order of solenoids activations similar to D. Kern et al. (2009) or Hwang and Ryu (2010). TWGs advantage over D. Kern et al. (2009) and Hwang and Ryu (2010) is far less interference of single solenoid activations on adjacent steering wheel areas compared to resonating vibrations.

Shakeri, Brewster, et al. (2016) as well as Shakeri, Ng, et al. (2016) experimented with different positions of solenoids, i.e. radial and perpendicular to the front of the steering wheel rim. They relied on findings from Fransson-Hall and Kilbom (1993) that the thenar region of the palm is best suited for pressure stimulation for their first prototype. This inspired two different versions of first paper prototypes of TWG. Fig. 3.1 shows a possible assembly of solenoids around the steering wheel rim with the pins extending in the direction of the driver. Fig. 3.2 shows the concept with the pins extending radially out of the steering wheel rim.

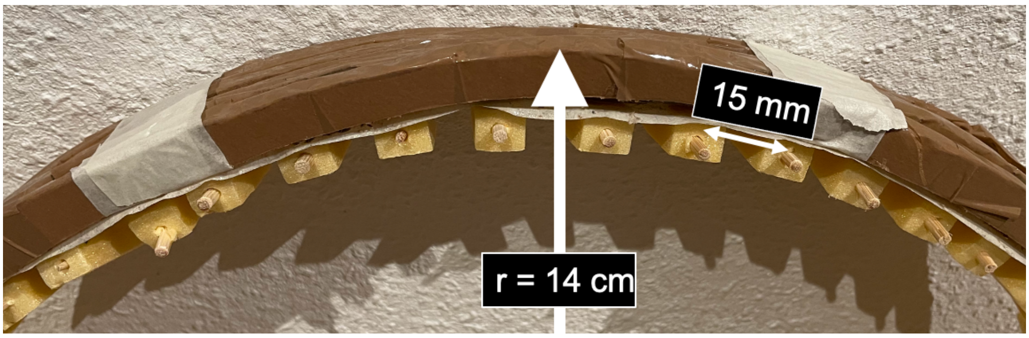


Figure 3.1: *Prototype of solenoids arranged with the pins extending towards the driver.*

Shakeri, Brewster, et al. (2016) recommend to not apply the solenoids pressure to the finger tips. The finger tips are the most sensitive part of the hand but pushing against them might loosen the grip on the steering wheel. The two versions only differed with respect to the requirements A-v and C-v. Regular solenoids are not cubic but have one distinctly longer side (Fig. 3.3). This length fits the width of a conventional steering wheel rim but not it's depth. Requirement A-v means TWG needs to come as close as possible to a regular steering wheel to be usable for different anthroprometric hand proportions. The

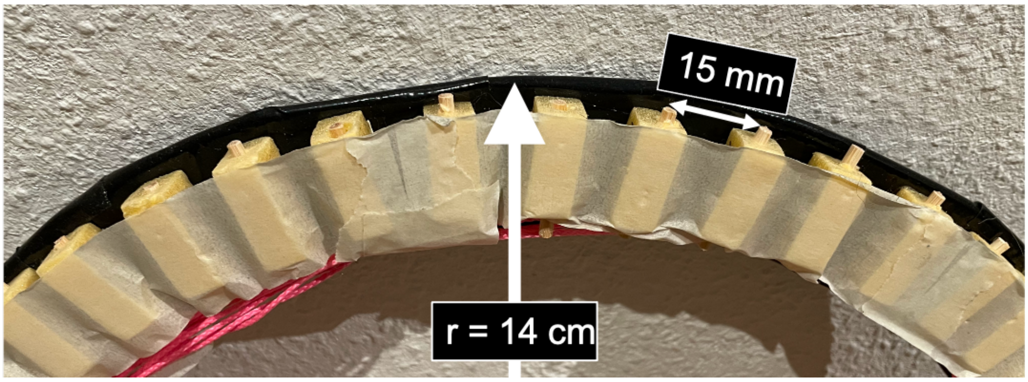


Figure 3.2: *Prototype of solenoids arranged with the pins extending radially outwards.*

perpendicular solution would have impacted the two requirements which is why the choice was to continue with the concept with radial pin extension.

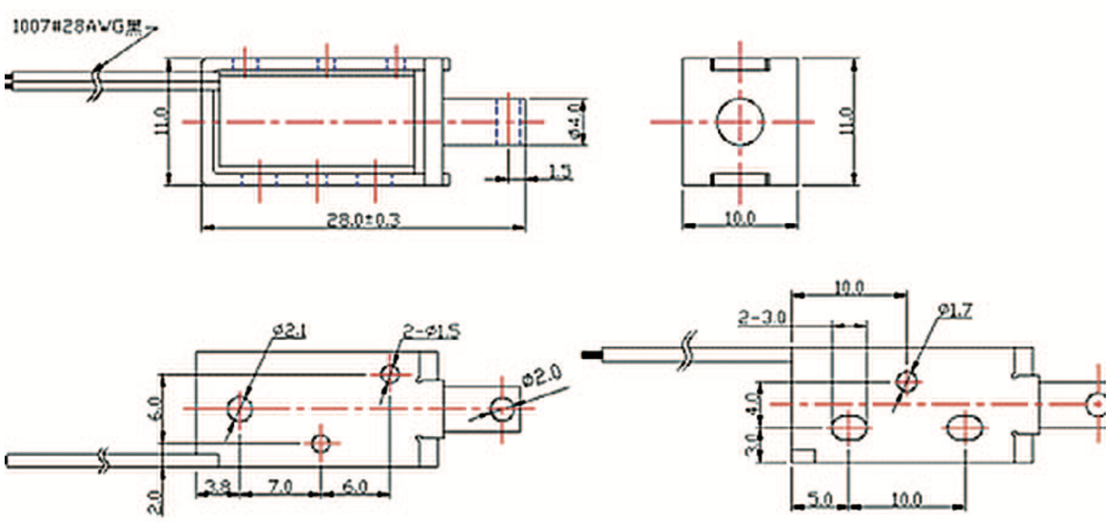


Figure 3.3: *Schematics of the solenoid ITS-LS 1110b. (Fig.from RED MAGNETICS powered by Intertec)*

The first prototypes already incorporated requirement A-iii. Hwang and Ryu (2010) spaced their actuators 20 mm apart while relying on Weinstein (1968) for the two-point threshold of 10 mm for the palm. The solenoids pins in TWG are spaced 15 mm apart. TWG was designed with a radius of 14 cm which is equal to the regular production steering wheel of a BMW Series 6 (E64) (Fig. 3.2).

3.1.3. New developments

TWG uses several specific developments that have not been discussed in the literature yet, although some scenarios are similar to designs of other studies. This thesis uses the solenoid ITS-LS 1110b from RED Magnetics powered by Intertec (Fig. 3.3). It weighs only 10 grams and works with voltages between 12 V and 24 V. This solenoid comes with the benefit of low weight, compact dimensions and low power supply. Fig. 3.4 shows the force-stroke diagram of the solenoid, indicating four different power levels with increasing indentation depth. A single solenoid has one line for voltage supply and one line for ground. If the two lines are connected to a power source between 12 V and 24 V the pin of the solenoid is extended with the force according to fig. 3.4. 12 V equal 1.1 W while 24 V equal 4.4 W. 2.2 W are reached with a voltage of 18 V.

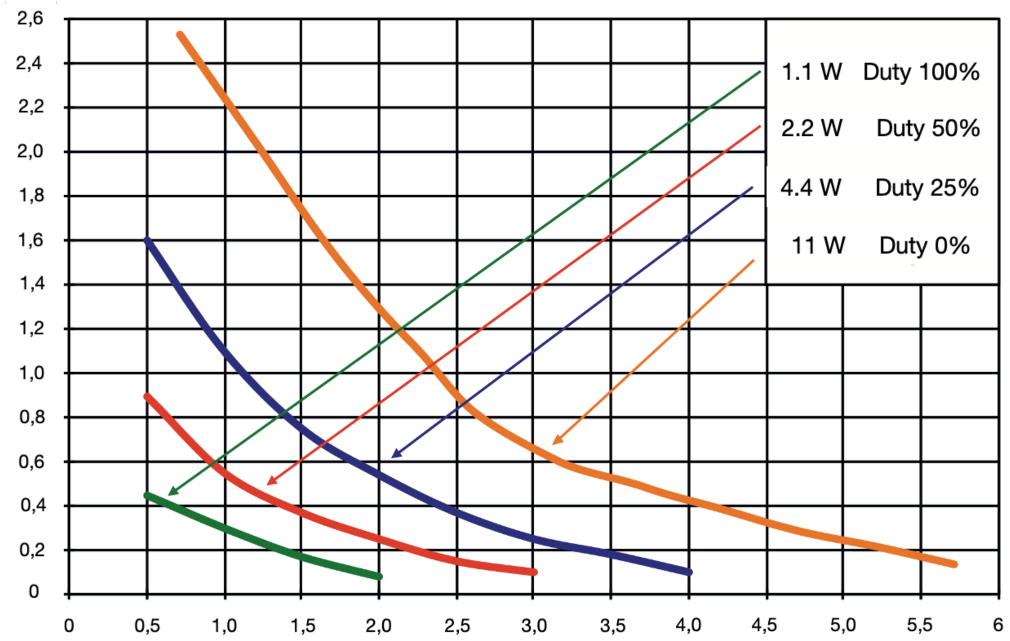


Figure 3.4: *Force-stroke-diagram of the solenoid ITS-LS 1110b. (Fig. from RED MAGNETICS powered by Intertec)*

For TWG the solenoids are activated using transistors which have three connection ports, two of which are connected to the solenoids power lines. The transistor is continuously connected to a 12 V power source and the accompanying ground. Current is only flowing through the transistor and to the solenoid when the third connection of the transistor receives a small voltage, also known as a "high" signal, compared to a "low" signal when no voltage is active. This signal is provided by an Arduino micro controller which can be programmed to supply the signal only when certain conditions are met (requirement B-iii). A detailed schematic of the electric connections can be found in Titze (2018). The micro controller also ensured the connection of TWG to other systems like a driving simulator software (requirement B-iii).

TWG uses 24 + 24 solenoids that each cover 90° of the steering wheel on the left and the right side. This is a compromise between requirements C-iii and C-iv. Fourty-eight solenoids with two electrical lines each come with 96 lines. This number of lines or even more could at some point get tangled up and interfere with free steering wheel rotation (Fig. 3.5). Yet 48 solenoids are still able to cover half of the steering wheel with much room for individually different gripping positions. Fig. 3.6 shows a 3D CAD model of TWG before the physical prototype for the first evaluation was manufactured.

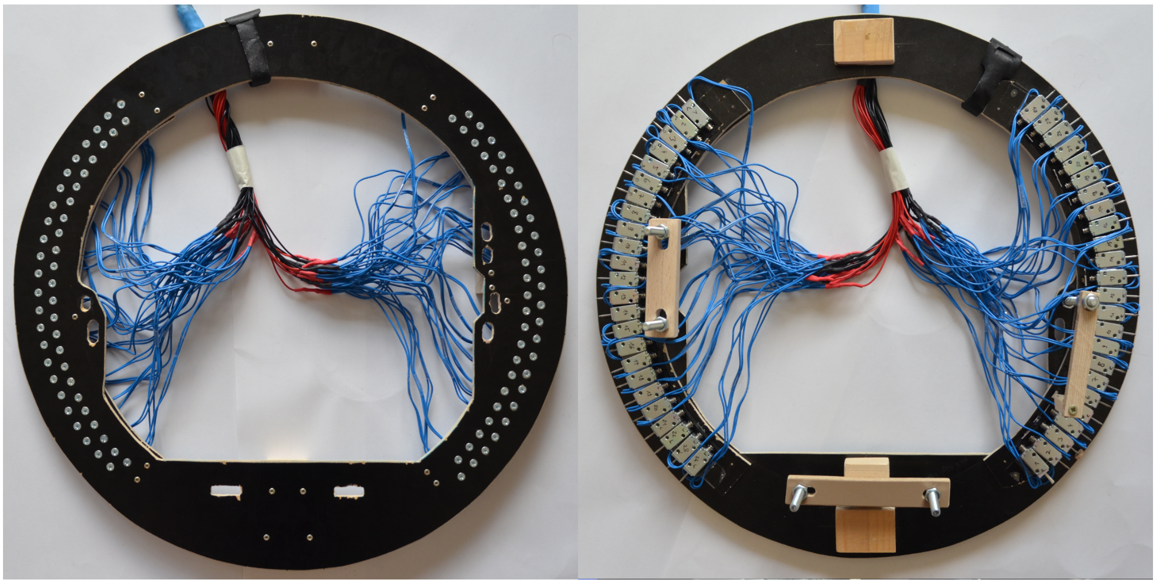


Figure 3.5: *Wooden TWG prototype with 48 solenoids mounted on a wooden base plate. Two screws for fixation per solenoid can be seen on the left. The cable routing of the 96 power lines can be seen on the right. (Fig. taken from Titze (2018))*

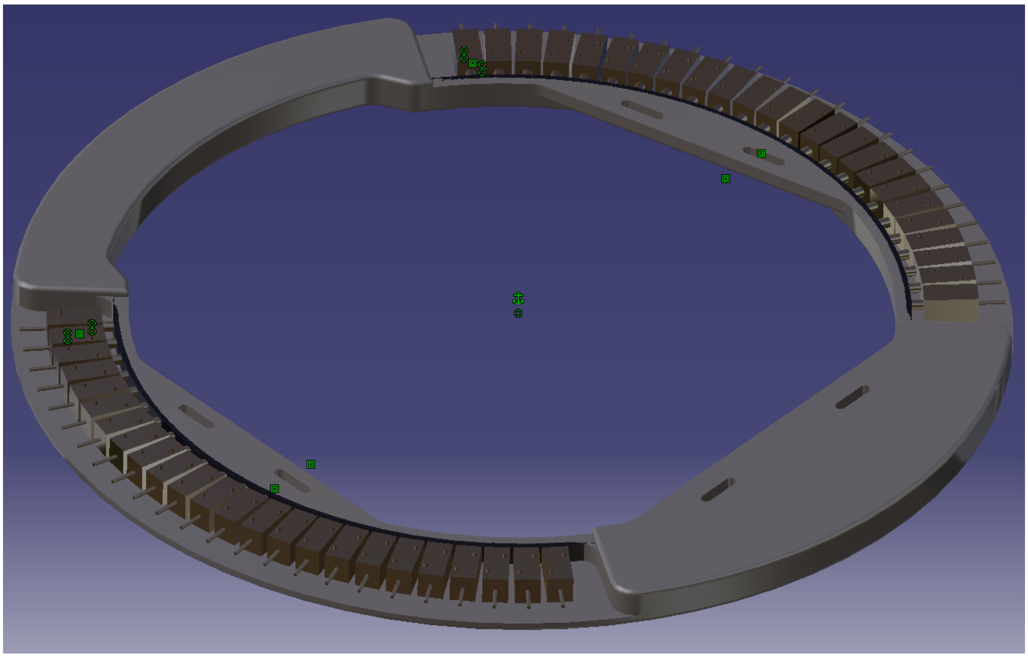


Figure 3.6: *CAD model of 48 solenoids mounted on a steering wheel base plate made of polyoxymethylene (POM) (Fig. taken from Titze (2018))*

The number of solenoids would've led to a very complex electrical circuit, considering that each solenoid would need its own transistor and other components. Yet results from Hwang and Ryu (2010) already indicated that it might be useful to have a set of actuators always run simultaneously and thereby create several identical dynamic patterns at the same time. This would reduce the time it takes for a pattern to reach the driver, finish, restart and reach the driver again. While one pattern "runs out", a second different could already be ready to contact the driver. A third one would just start at the same time and ensure a continuous stimulation after the second pattern ends. That's why the 48 solenoids were combined into sets of three, effectively also reducing the number of electrical components needed for the circuit to a third (Fig. 3.7).

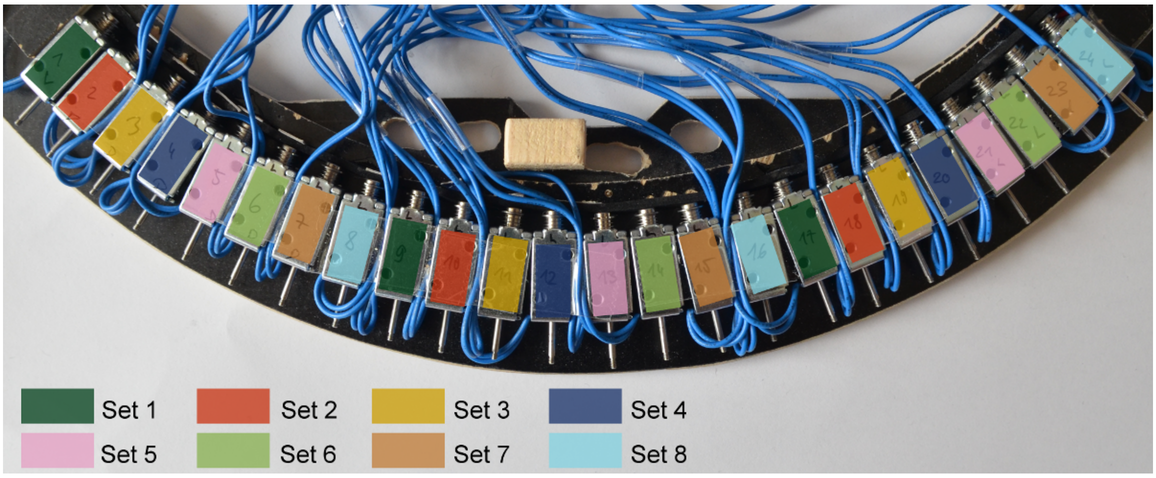


Figure 3.7: *Twenty-four solenoids with color indication of sets of three. (Fig. taken from Titze (2018))*

The dynamic patterns for TWG followed the idea from Hwang and Ryu (2010). Neighboring solenoids were activated in sequence, creating the impression of a wave of contact points traveling down the side of the steering wheel. Because three solenoids made up a set, there were always three waves traveling in equal distance at the same time.

3.1.4. Evaluation

The first prototype of TWG was evaluated in a study by Keppler (2019). This work included TWG still in in the form of an add-on for an existing steering wheel. The goal of the first evaluation was to collect user feedback on whether TWG was able to produce the intended stimulations and what information drivers took from them. Keppler (2019) also investigated TWG for functions in take over scenarios during highly automated driving as well as longitudinal maneuver information. This subchapter only focuses on the evaluation aspects of lateral assistance.

TWG prototype

Fig. 3.8 shows the TWG prototype with all components used in the study by Keppler (2019). The 48 solenoids were mounted on a base plate made of polyoxymethylene (POM). This synthetic material ensured the steadiness, lightness and safety of contact with hands for the prototype (requirements B-iv and C-ii from tab. 3.1). The 96 power lines were combined in one large spiral cable which was the first step to make sure drivers would not get tangled up in the lines (requirement B-ii).

Keppler (2019) used two different configurations for the wave pattern, which are defined by the delay t_{delay} between two neighboring solenoids being activated: 180 ms and 80 ms. Shakeri, Brewster, et al. (2016) covered their solenoids with a latex cover to increase the contact area. Any type of cover decreases the power that reaches the skin because the materials elasticity needs to be overcome first. Keppler (2019) tested different pin caps and installed plastic caps with a $1\ cm$ diameter that increased the pressure area

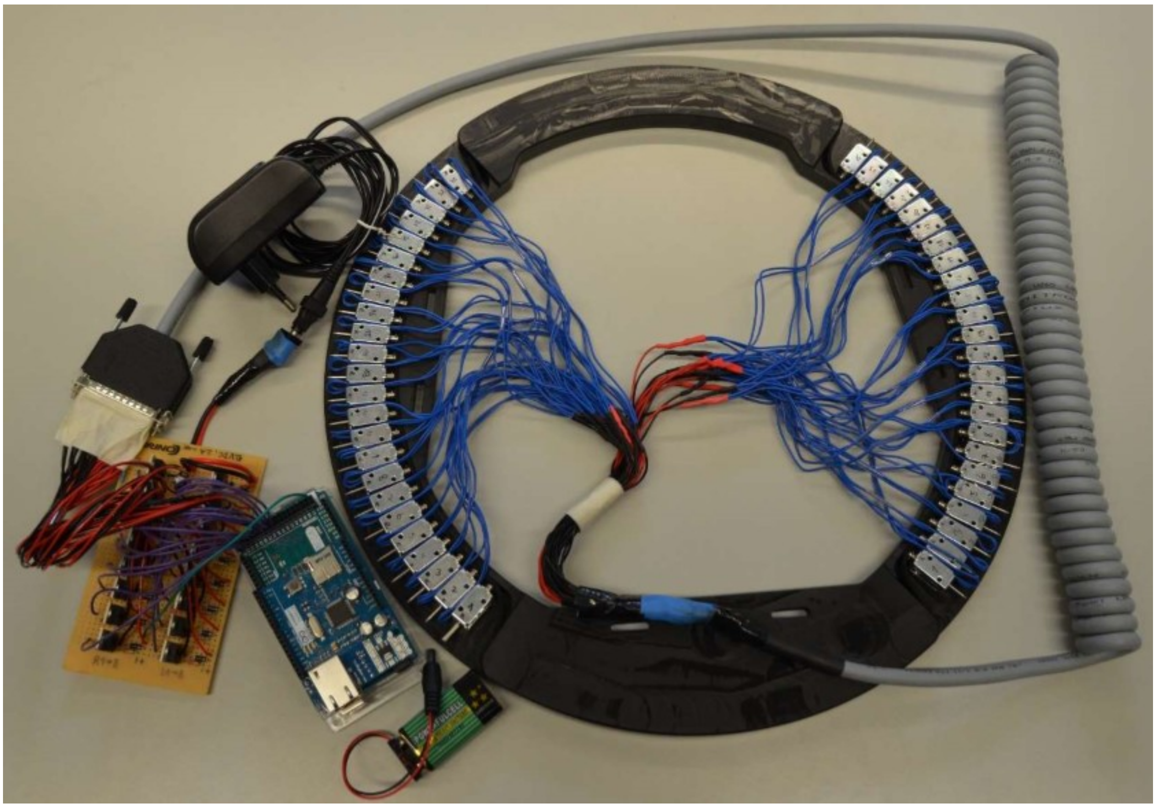


Figure 3.8: *Prototype of TWG as used in the first study: Solenoids mounted on a base plate, spiral cable including 96 power lines, connection ports to the electrical circuit, Arduino micro controller, wall plug as power source for the solenoids and a battery as power source for the micro controller. (Fig. taken from Keppler (2019))*

of each solenoid without decreasing the usable solenoid force (Fig. 3.9). The size of the plastic caps created an almost continuous surface on top of the solenoids pins.

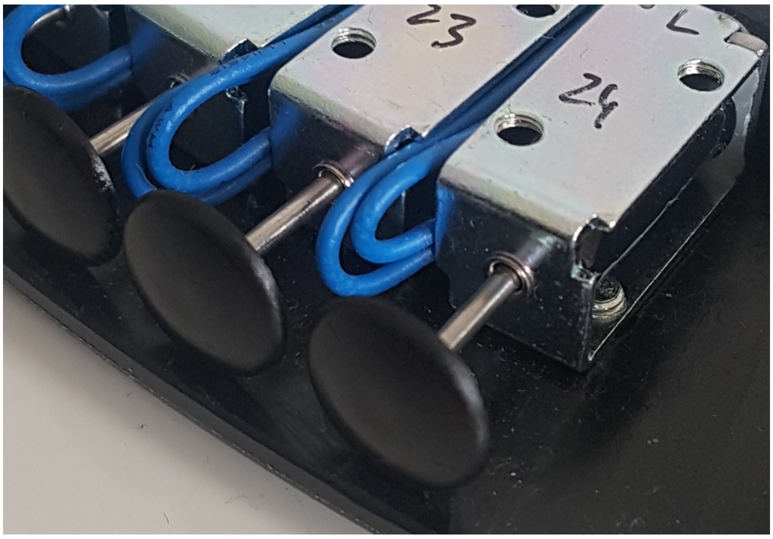


Figure 3.9: *Close up view of the plastic caps installed on the solenoids pins. (Image taken by Christofer Keppler)*

Results

Thirty participants (24 male, 6 female, ages 20 to 58) experienced TWG in a BMW Series 6 (E64) Mockup. They saw static driving scenarios on a single large scale canvas in front of the vehicle. TWG was activated with different functions fitting the shown scenario for several seconds. In addition, participants experienced TWG functions that created the wave of stimulations traveling down the side of the steering wheel with their eyes closed to eliminate this sensory channel as source of feedback.

Key messages for improvement from participants included:

- **More powerful solenoids.** This showed that requirement A-ii perceptibility needed improvement.
- **More solenoids.** This was another indication that perceptibility was not sufficient yet.
- **Adjust the solenoids power for each urgency.** The solenoids power was fixed at the default value of $1.1\ W$ for the entire evaluation.
- **Include TWG in a proper steering wheel instead of an add-on.** This supported the initial plan to build an entire steering wheel prototype and was expected at this point of the development process.
- **Difficulties in recognizing the wave pattern or the waves direction.** This was most likely due to the problems with properly perceiving the solenoids pressure points.
- **Increase the contrast between different wave speeds.** This could have been another result of poor perceptibility or a genuine request even with proper solenoid power.

Participants feedback initiated the first improvement iteration of TWG. Not all aspects were improved at once because some relied on others.

3.2. Improvement Iteration One

The first constructive improvement was performed as part of a student thesis by Bahri (2019). This step focused on implementing TWG as its own proper steering wheel. While other possible changes from chapter 3.1.4 remained in focus, an improvement in grip had the biggest potential to raise perceptibility without further technical adjustments of the solenoids.

TWG prototype

TWG had one side with the solenoids being exposed when the system was not mounted on a separate steering wheel. The other side was a flat surface from the base plate the solenoids were mounted on. A cover for the open side was designed that also included a curved surface (Fig. 3.10). The curvature resembled the roundness of a regular steering wheel in comparison to a flat surface. TWG also needed a center component that could be mounted on a steering column. A thin metal sheet was designed that included holes for screws to be fixed on the steering column, long holes to be connected with the base plate and a three spokes design (Fig. 3.11).

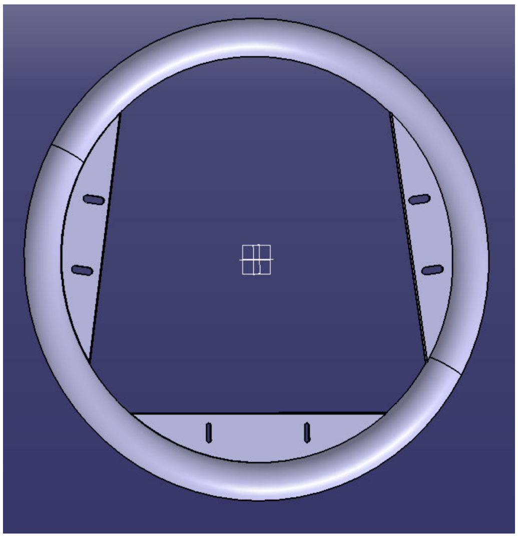


Figure 3.10: *3D model of the new front cover with a curved surface. (Fig. taken from Bahri (2019))*

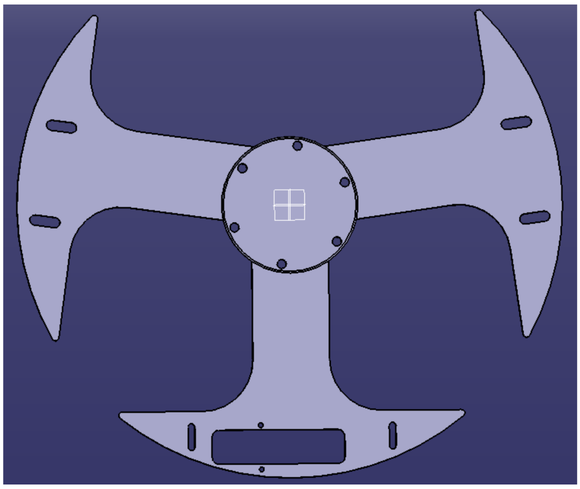


Figure 3.11: *3D model of the new center component with holes for fixing it with TWGs base plate and a steering column. (Fig. taken from Bahri (2019))*

Fig. 3.12 shows the assembled TWG system while fig. 3.13 shows the prototype mounted in a seat bucket driving simulator. The evaluation from chapter 3.1.4 was repeated with this improved prototype. To eliminate even more non-tactile perceptions, participants had to wear ear pods that played a recording of the solenoids activation sounds as a distraction. The speed of the recorded activations was halfway between the used speeds in the evaluation with $t_{delay} = 130\ ms$ between individual activations. This way subjects should be forced to rely on tactile stimulations to correctly identify the speed of the wave pattern. Other studies had used similar approaches to eliminate acoustic perception like white noise (Hwang & Ryu, 2010) or music/spoken words (D. Kern et al., 2009).

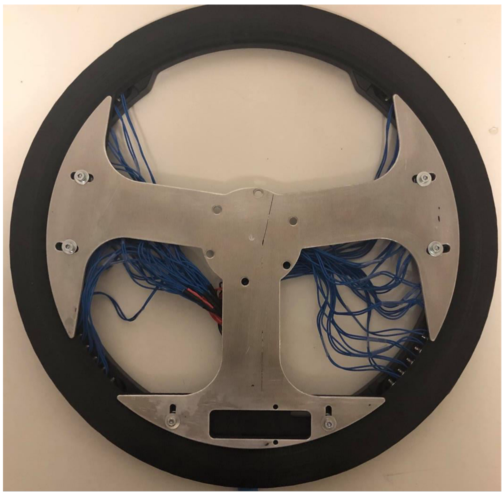


Figure 3.12: *Image of the prototype for the second evaluation. The new three spoke center plate is fixed with screws onto the base plate. (Fig. taken from Bahri (2019))*

Figure 3.13: *Setup of the second evaluation: TWG mounted in a seat bucket. (Fig. taken from Bahri (2019))*

Results

Twenty-two participants (16 male, 6 female, ages from 22 to 27) experienced TWG in a seat bucket driving simulator (Fig. 3.13) that allowed proper mounting of the prototype on the steering column. They saw static driving scenarios on three HD TVs in front of their car seat. TWG was activated with different functions fitting the shown scenario for several seconds. In addition, participants experienced TWG functions with their eyes closed to eliminate this sensory channel as source of feedback.

Key messages for improvement from participants included:

- **A rounded back like on the front.** The newly designed front part with a curvature increased TWGs resemblance of a regular steering wheel. Participants recommended to copy this feature also to the so far flat back side. This way TWG also grew in overall thickness.
- **Approx. 75% of subjects correctly identified a wave pattern and the difference in wave speeds.** Only 50% correctly identified the wave direction which was top to bottom. This means other parameters besides the already improved physical appearance needed to be adapted as well to increase full perception of the applied patterns.
- **The spokes prohibited proper placement of the thumb.** A regular gripping position is essential for steering and the perception of TWG. The spokes were larger than mechanically necessary which is why an adjustment with reducing material was feasible for the next evaluation.
- **Stronger and more solenoids were mentioned again to improve perception.** This underlines the necessity to adjust the solenoids configuration in addition to the change in TWGs physical appearance.
- **Increase the difference between the two wave speeds to make them distinguishable easier.** The delay parameters that control the wave speeds were set based on the best of the authors knowledge so far. A proper evaluation of the precise values became necessary.

Participants feedback initiated the second improvement of TWG. This was the last planed refinement of all physical components before configuration parameters were tackled to ensure proper perception for this works research question.

3.3. Improvement Iteration Two

The second constructive improvement was performed as part of a student thesis by Broers (2019). This step focused on preparing the physical prototype for usage in driving simulator studies. It includes the construction of the desired back part of the TWG as well as safety improvements.

TWGs solenoids undeniably produce sounds when activated. The evaluation in chapter 3.2 tried to eliminate sound as an information source with added artificial sounds. A more basic approach was to eliminate the source of the sounds itself. Both the extension of a solenoid pin as well as the retraction lead to metal on metal contact which produces the characteristic sound of the solenoids. To avoid this, the circlip on one end was replaced with a rubber sealing ring and the other side of the pin was encased with a foam tube that cushioned the retraction of the pin (Fig. 3.14).

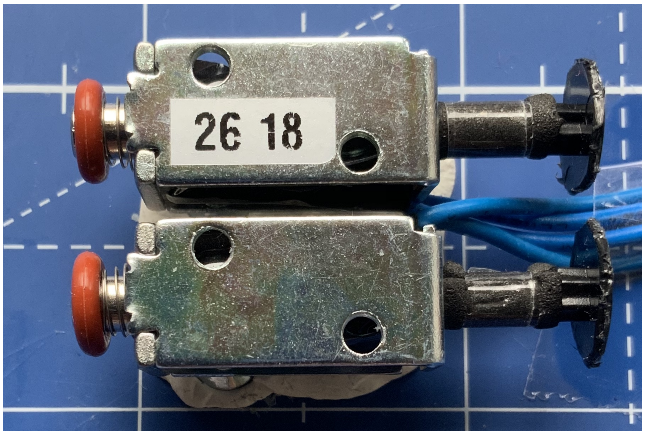


Figure 3.14: *Close up view of two solenoids with the red sealing ring on one end and the foam tube around the pin on the other side. (Fig. taken from Broers (2019))*

Broers (2019) showed that these adjustments led to improvements of noise emission in the spectrum of $3000\ Hz$ and higher. Unfortunately this effect was only valid for an operating voltage of $12\ V$. At $18\ V$ the effect was almost completely gone.

Safety was a key requirement from the beginning (Tab. 3.1 B-iv). Up to this point the microcontroller and the electrical circuit were not covered and could come in contact with skin by accident. Broers (2019) documents the development and production of a 3D printed case for all electrical parts apart from the solenoids (Fig. 3.15).

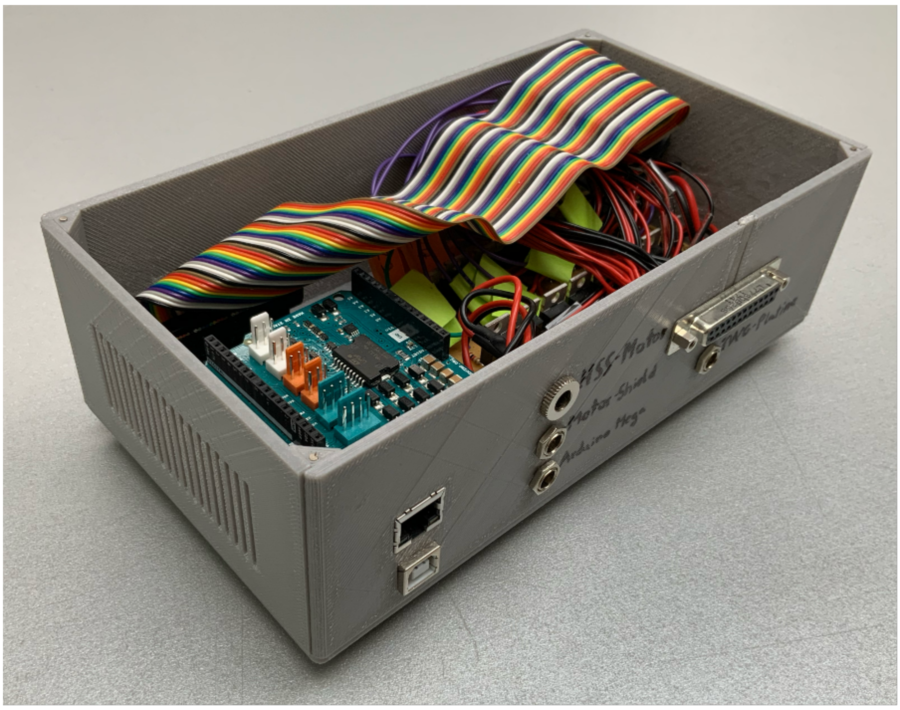


Figure 3.15: *3D printed casing for the Arduino micro controller and the electrical circuit. (Fig. taken from Broers (2019))*

The next adjustment reduced the number of cables. Twenty-four solenoids on one side had 48 cables, 24 for voltage and 24 for ground. All solenoids share the same ground which is why these 24 cables could be reduced down to one single cable. Yet each solenoid had its own connection to ground. A custom made circuit board was installed to replace the cables with tracks on the board (Fig. 3.16).

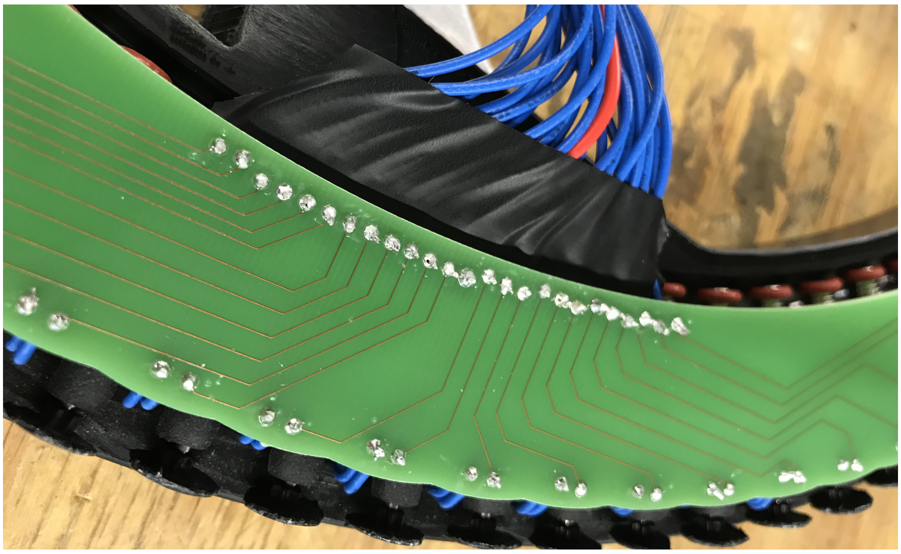


Figure 3.16: *Custom made circuit board mounted on top of the solenoids. (Fig. taken from Broers (2019))*

The final improvement combined two results from chapter 3.2 as well as one last safety issue. The back side of TWG got a rounded surface like the front. In addition, some material was removed at the thumbs gripping position. The depth of the back side was increased behind the two horizontal spokes. This created space to store the remaining cables on both sides. These cables were taped together per side starting at the exit point where they left the back of TWG (Fig. 3.17).

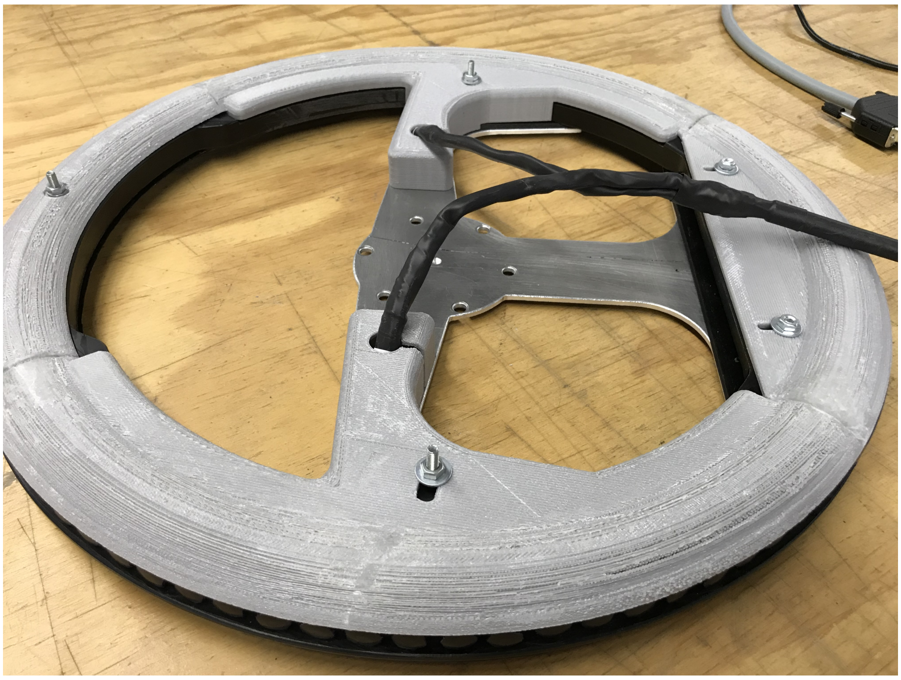


Figure 3.17: *Back view of the final prototype with the taped together solenoid cables in black. (Fig. taken from Broers (2019))*

4. TWG Studies

4.1. Study One - Perception of TWG

The goal of this first study was to gain insight on specific parameters of the systems control before deploying the tactile system together with HSC in a following study. Another goal was to bring the system into an active driving context after the previous evaluations worked with static environments. A simple driving simulator study was setup and TWG, as designed in chapter 3.3, was used as a simple lane departure warning system. Although this was never its intended use, it allowed for several specific parameters to be tested, i.e. pattern, activation speed and steering wheel sides. Selected results were published in Kalb (2021).

4.1.1. Study One Setup

Physical setup

The study was conducted in a regular lab room at the chair of ergonomics at TUM in July and August 2020. Due to covid-19 regulations the study was simplified and adjusted to safety measurements. A single participant and the experimenter were seated at separate tables approximately 2 meters apart. The experimenters table was equipped with different computers and displays to control the experiment (Fig. 4.1). The participants table was equipped with a single 24" HD 16:9 ratio display. This displayed the simulated driving track during the experiment. The base of a Logitech G27 gaming steering wheel was mounted on the edge of the table on the opposite side of the display. The base was stripped of it original steering wheel rim and replaced with the TWG system. Participants sat on a height adjustable office chair with a 5-wheel base with the TWG system in front of them and facing the screen. The table itself was also height adjustable. A set of three pedals was placed under the table to complete the set of control elements (Fig. 4.2). Participants had to wear noise cancelling headphones (Bose QuietComfort 35) that played static white noise during all active phases of the experiment, similar to the studies from Hwang and Ryu (2010) or Enriquez et al. (2001). The headphones could be taken off in intervals, i.e. changing to the next experiment phase or during questions.

Participants were only allowed to touch surfaces that were absolutely necessary for the experiment. That included the TWG system, the chair and the table. All questionnaires were filled in an interview style by the experimenter who read questions out loud and wrote down answers at his table. All surfaces were disinfected between participants. Participants could decide individually to take off their protective face mask while the experimenter wore his during the entire experiment. The TUM ethics committee raised no objection to this study one. All participants signed informed consent forms.

Questions and answers were documented using LimeSurvey. SILAB 6.0 was used as driving simulator software. The connection between SILAB and the Arduino micro controller activated and deactivated the

TWG system. Despite the best intentions and actions it was not possible to get information on the force feedback function of the Logitech G27 steering wheel. Neither the German nor the American customer services were able to provide information on what torques were applied at what steering angle. The behavior can best be described as a linear relation of steering wheel angle and force feedback between -45° and +45° with a steep ramp up from there on, based on expert feedback at the chair of ergonomics.

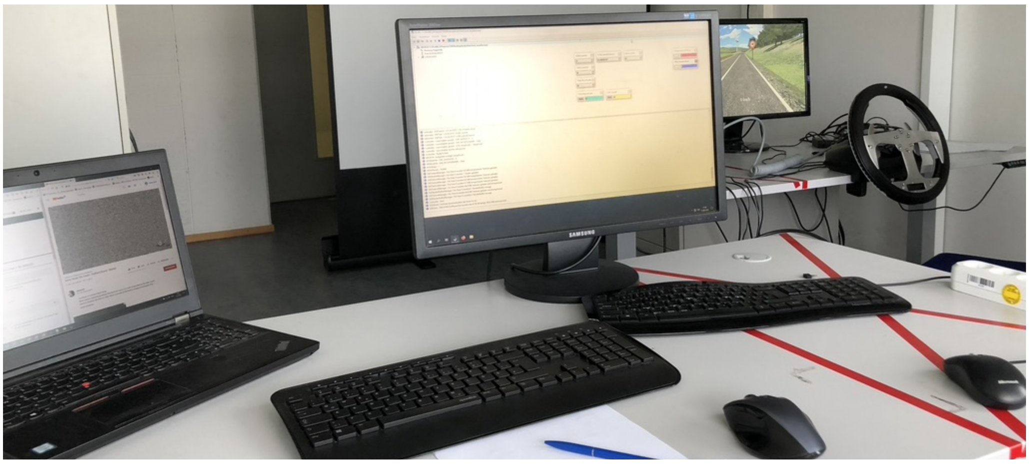


Figure 4.1: *View from the experimenters position with the experimenters table in the front and the participants table in the back.*

Figure 4.2: *Participants table with the display, TWG on the Logitech G27 base, pedals unter the table and chair on the right.*

TWG as assistance system

TWG was used a lane keeping system in this study. Fig. 4.3 shows TWGs configuration and action according to lateral driving performance, i.e. the position of the vehicles center of gravity (COG). TWG was not active in a dead-band of $60\ cm$, $30\ cm$ to the left and $30\ cm$ to the right of the lane center. TWG was activated and remained active if the vehicles COG was between $30\ cm$ and $50\ cm$ off of the lane center.

The delay parameter t_{delay} was set to $50\ ms$ in this area. The delay describes the waiting times between individual solenoid activations in the patterns described below. TWG shut off if the vehicles COG came back within the dead-band. The delay was decreased to $35\ ms$ if the vehicles COG exceeded a deviation of $50\ cm$ off of the lanes center. TWG remained active during the transmission from $t_{delay} = 50\ ms$ to $t_{delay} = 30\ ms$. A decreased delay can also be described as an increased frequency. TWG shut off completely again if the vehicles COG exceeded the lanes boundaries, i.e. a deviation larger than $1.75\ m$ (half of the lane width of $3.5\ m$). The delay parameters of $35\ ms$ and $50\ ms$ were loosely based on the configuration from Hwang and Ryu (2010) in this study after much higher values in chapters 3.1.4 & 3.2 yielded no clear results yet.

If the COG was within an area where TWG should be active, a single run of a pattern was triggered. The pattern was always finished before the system reevaluated if another one had to be run, i.e. if the COG was still in an area where TWG should be active. The pattern was also finished if the COG came into the dead-band in the middle or exceeded the lane markings to the left or right , i.e. areas where TWG should not be active, during a pattern run.

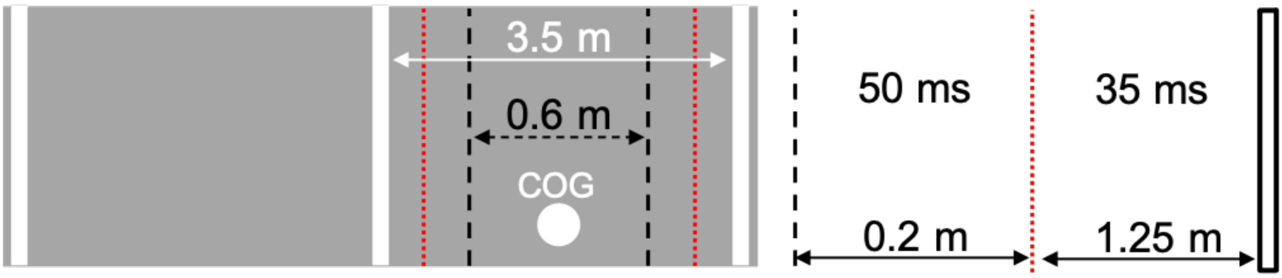


Figure 4.3: *Areas of activations of TWG with corresponding delay times. TWG stays off within a dead band of* $60\ cm$. *More deviation leads to TWG activation with* $t_{delay} = 50\ ms$. *The delay decreases to* $t_{delay} = 35\ ms$ *if the deviation exceeds an additional* $20\ cm$. *TWG shuts of if the COG crosses the lane marking.*

Procedure

There were three separate parts of the experiment that each participant went through. The **first part** was formalities and a first demographic questionnaire. Participants generated an individual pseudonym to name their data. Demographics included age and gender as well as prior experience with lane keeping driver assistance.

The goal of the **second part** was to identify the best suitable power level for solenoid activations, going back to feedback from chapter 3.1.4. This was controlled via different voltages. The tests included activations of the TWG system at $12\ V$ $(1.1\ W)$, $18\ V$ $(2.2\ W)$ and $24\ V$ $(4.4\ W)$ at each hand separately as well as participants feedback about perception. Participants did no driving in the simulated environment during the second part but had the chair and table adjusted so that they could grip the steering wheel in an individually fitting driving posture. Their hands hat to be positioned at the 9/10 and 2/3 o'clock position with the individual grip, i.e. how far around the rim the hands and fingers reached, being up to the participant. Table 4.1 gives a chronological overview for all activations per participant. All participants had the same order of activations. For each activation, e.g., left hand $12\ V$, the solenoids extended five times with

$t_{delay} = 200\ ms$ in between. Repetitions of an activation was possible upon request, but only asked for once. The activation was designed so that each participant could experience exactly two solenoid touches at the same time. They were asked after each activation how many separate points of contact they felt and how certain they were on a likert scale from 1 (very uncertain) to 5 (very certain) that their answer was correct. The experimenter provided no feedback to participants answers until the end of the entire first part. Participants had to wear the headphones playing static white noise and their eyes closed during activations of TWG.

Table 4.1: *Order of tests for all participants in the second part of the first TWG study. Every test was directly followed by a questionnaire.*

Order	1	2	3	4	5	6
Hand	left	left	left	right	right	right
Voltage	$18\ V$	$12\ V$	$24\ V$	$18\ V$	$12\ V$	$24\ V$

Participants drove four identical simulated tracks in the **third part** of the study. The tracks only differed in the configuration of the TWG system, also referred to as *pattern*:

1. ***Simple Contra***: Solenoids were split into two groups per side of TWG. If activated, an entire group of solenoids would extend at the same time. After the delay ($50\ ms$ or $35\ ms$) the solenoids retract again and the other group extends simultaneously. One activation was completed once the second set of solenoids was fully retracted, which was after $100\ ms$ (= $2\ x\ 50\ ms$) or $70\ ms$ (= $2\ x\ 35\ ms$). The pattern was always activated at the side of the deviation, meaning drivers had to steer away from the stimulus, which is also called contralateral (Petermeijer, Bazilinskyy, Bengler, & de Winter, 2017).

2. ***Wave Single Contra***: Solenoids are activated according to the sets of three in which they are hardwired. The first set of three solenoids extends and remains extended for $t_{delay} = 50\ ms$ or $t_{delay} = 35\ ms$. The next set is extended while the first set retracts simultaneously after the delay. The following set is always the one above the preceding one. This process creates three waves of extensions upwards along the steering wheel rim. One activation was completed once all eight sets were activated exactly once, which lasted $400\ ms$ (= $8\ x\ 50\ ms$) or $280\ ms$ (= $8\ x\ 35\ ms$). The pattern was always activated at the side of the deviation. A wave running upwards on the left side of the steering wheel creates the impression of a clockwise rotation (steering to the right) which is the desired turn of the steering wheel to cancel out a deviation to the left.

3. ***Wave Double***: This patterns followed the basic same scheme of *Wave Single Contra*. It was activated on both sides of the steering wheel regardless of the side of the deviation. The main difference is the opposite directions of the waves. For a deviation to the left, i.e. a required right turn, the wave on the left side ran upwards while the wave on the right side ran downwards. This created the impression of a clockwise rotation which is the desired turn of the steering wheel to cancel out a deviation to the left. The directions were inverted when the deviation of the COG off of the lane center was to the right.

4. ***Baseline***: TWG was never activated during this drive. It served as a comparison for possible investigations of driving performance. It also checked whether participants falsely reported random activations and perceptions during later questionnaires which could weaken the validity of their answers in the other three drives. No participant should report any activations during this drive.

The task was to steer the simulated vehicle within a two lane country road (one lane per driving direction, Fig. 4.4), while maintaining a speed of $100km/h$. The track consisted of 15 straight segments, seven curves to the left and seven curves to the right (Tab. 4.2 and Fig. 4.5). All segments were 300 meters long and the curves all had the same radius of 300 meters. Participants were asked to drive in the middle of their own lane as well as possible. They were also informed that their point of view in the simulation was positioned in the lateral center of the vehicle, in contrast to conventional vehicles where the point of view of a driver is either on the left or right seat. No vehicle parts were visible in the simulation to not give visible feedback about the current lateral position within the lane.

Each driver experienced the four drives in randomized order. Each drive started with the participants putting on the headphones that were playing white static noise. Then they put their hands on the steering wheel in a gripping position that would resemble the 9/10 and 3/2 o'clock positions. Drivers could decide themselves how to grip the steering wheel, e.g., how far around the rim they would reach. Drivers could start each drive by pressing the gas pedal. The end of each track was reached when "STOP" signs become visible on the road. At that point participants could take their hands of the steering wheel and take off the headphones.

Figure 4.4: *Participants view of the simulated track in the first study.*

Table 4.2: *Overview and order of track elements for all four identical drives.*

Orientation	Length m	Curvature m
Straight	300	
Right	300	300
Straight	300	
Left	300	300
Straight	300	
Right	300	300
Straight	300	
Left	300	300
Straight	300	
Right	300	300
Straight	300	
Left	300	300
Straight	300	
Left	300	300
Straight	300	
Right	300	300
Straight	300	
Right	300	300
Straight	300	
Left	300	300
Straight	300	
Left	300	300
Straight	300	
Right	300	300
Straight	300	
Right	300	300
Straight	300	
Left	300	300
Straight	300	

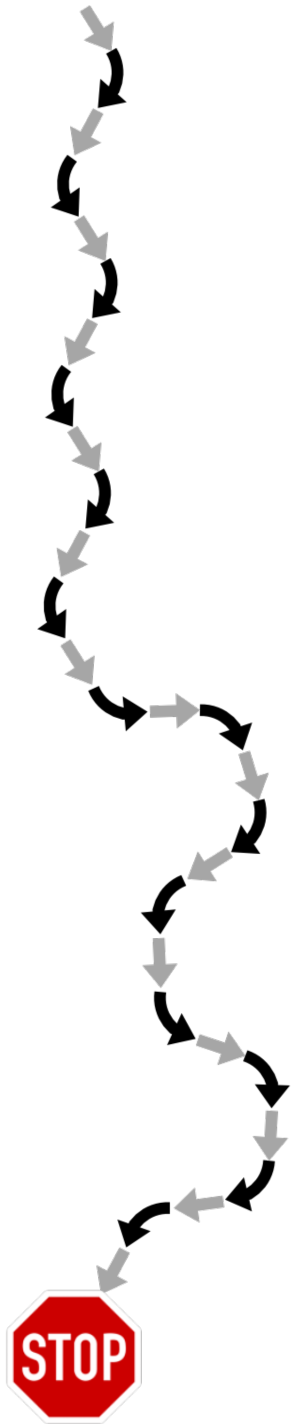


Figure 4.5: *Track overview with 300 m long straights (grey) and 300 m long left and right curves (black) with a radius of 300 m.*

Drivers only received instructions that the TWG system would support them in their task to drive in the middle of their lane. Patterns were not presented or practiced prior to the drives because a later questionnaire would ask for specific properties of the patterns and whether drivers were able to identify them. The track order was randomized between participants. Participants wore the headphones and listend to static white noise, even in the baseline track, to ensure equal conditions for all drives. Each drive ended with an interview by the experimenter.

The first question of the following interview was if participants had experienced any activity of the TWG system during the drive. Possible answers were "yes", "no" and "no answer". Only the option "yes" spawned several more questions. If the answer was "yes", the next question was how participants had perceived the TWG system: visually, acoustically, haptically/tactilely or in another way. Multiple answers were possible.

Next was an open question on what participants had perceived, e.g., when/in what scenarios did the system activate, how many points of contact did they notice, when and how? Participants answers were later sorted into the categories:

1. **Function**: Did participants correctly understand the design of the lane keeping assistance system?
2. **Side**: Did participants correctly identify the side or sides the system was activated on?
3. **Pattern**: Did participants correctly identify the pattern of solenoid activations (*Simple Contra*, *Wave Single Contra*, *Wave Double*) in all drives except baseline?
4. **Power**: How did participants rate the power level of solenoids activations?
5. **Speed**: How did participants rate the speed of solenoids activations, i.e. t_{delay}?

4.1.2. Results of Study One

Part one

Ten female and 13 male subjects participated in the study. The mean age was 28.1 years with a standard deviation of 2.2 years. All participants completed all parts of the experiment. Participants were fairly familiar with lateral assistance systems as 82.6% rated their prior experience with at least 1 on a scale from -3 to +3 (Fig. 4.6).

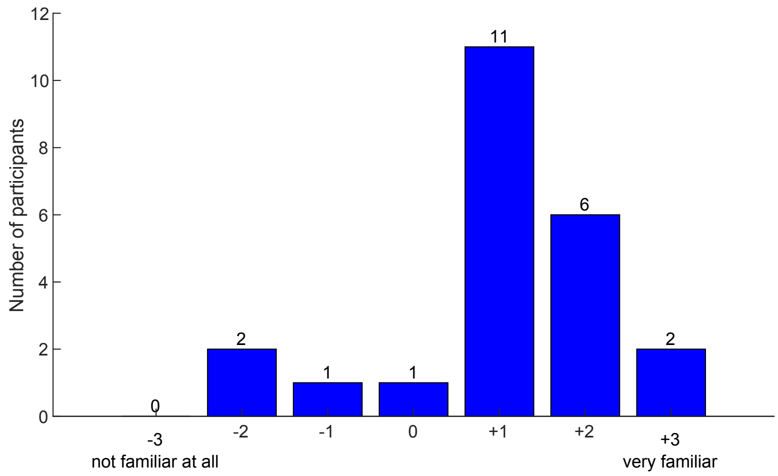


Figure 4.6: *Participants prior experience with lateral assistance systems in study one.*

Part two

Fig. 4.7 shows the answers of participants following activations on the left/right side for all three tested power levels. Answers of more than two contact points were all categorized as "more than 2". Every answer was accompanied with a rating of certainty by the subjects. These results are shown in fig. 4.8. Mean values are not directly comparable for every answer because the number of participants who gave that answer, also indicated in fig. 4.8, differed depending on the answer.

The answer with the highest count moved with increasing power from zero contact points via one contact point to two contact points for the left hand. One contact point was the most often answer for the right hand, only tying at $12\ V$ with zero contact points. The highest certainty for an answer was given for the left hand at $18\ V$, although this result is based on only a single answer.

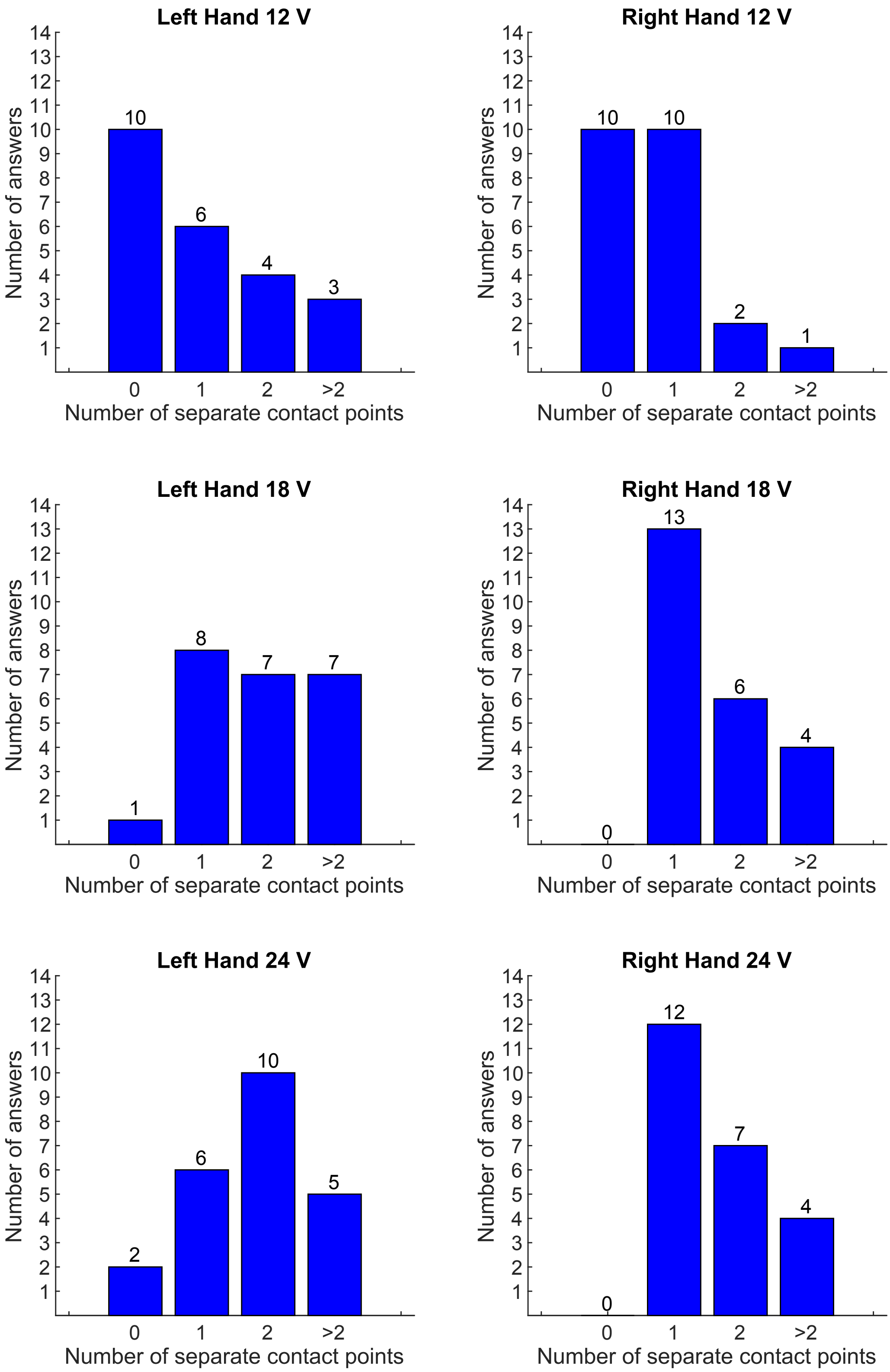


Figure 4.7: *Number of contact points reported by participants, divided into left and right hand and power levels of 12 V, 18 V and 24 V.*

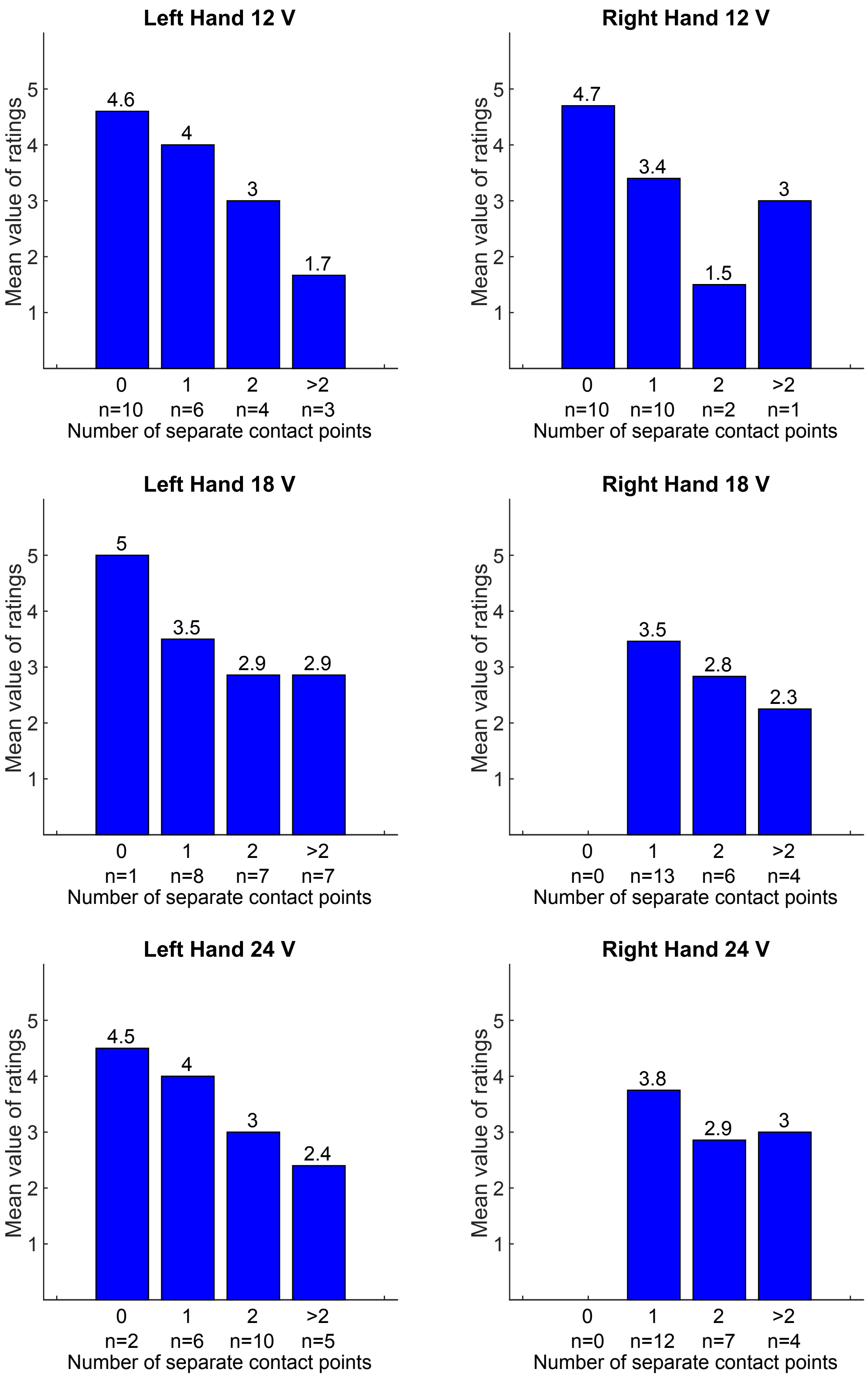


Figure 4.8: *Certainty of answers by participants, divided into left and right hand and power levels of 12 V, 18 V and 24 V.*

Part three

Sufficient activations were the basis for informed evaluations by participants. Fig. 4.9 shows the number of activations of TWG per track (*Simple Contra*, *Wave Single Contra*, *Wave Double*), speed ($t_{delay} = 50\ ms \mathrel{\widehat{=}}$ slow or $t_{delay} = 35\ ms \mathrel{\widehat{=}}$ fast) and hand/side. Only data from the 14 curves were analyzed because straight segments could be driven through without any steering activity.

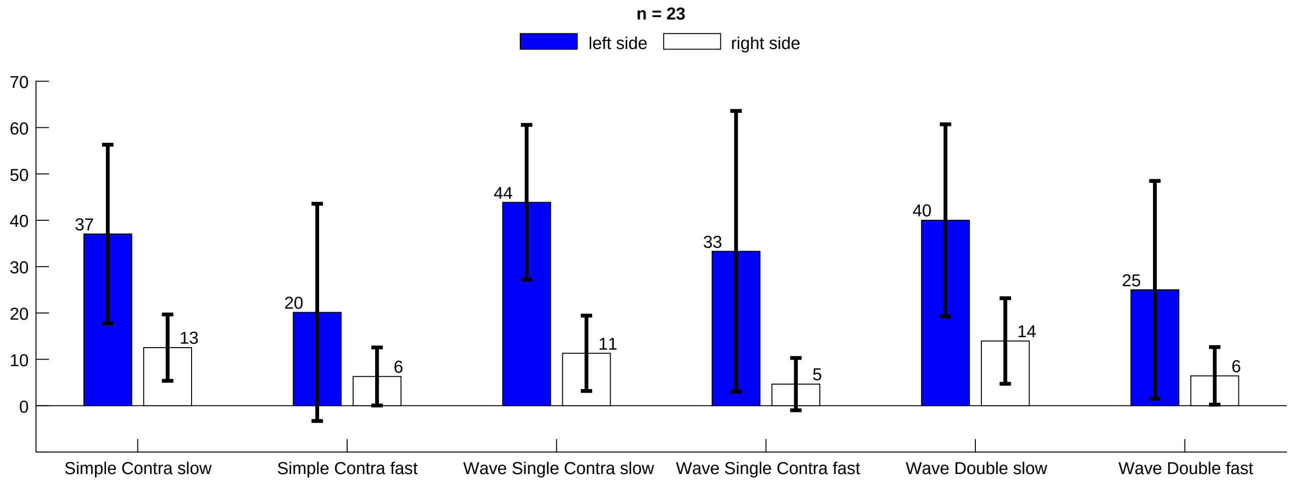


Figure 4.9: *Mean number of activations divided by track, side and speed with error bars indicating ±1 standard deviation.*

An activation was always counted at the onset of the respective pattern. The system reevaluated the COGs position after each completion of an activation. The pattern was started again if the criteria depending on the COGs position were still or again fulfilled. It was possible for drivers to leave an active area of lane assistance (see Fig. 4.3) while a pattern was running, but the pattern would then still finish. So the number of activations in fig. 4.9 represent the number of individual points in time where the COG was in an active area and no pattern was currently running (because a previous one just finished or because the COG just moved into the active area), which would then lead to a new activation of the system.

The mean number of activations on the left side of the steering wheel exceeded the mean number of activations on the right side in all drives and speeds. Opposite exceptions occurred in four cases for *Simple Contra slow*, in seven cases for *Simple Contra fast*, in one case for *Wave Single Contra slow*, in one case for *Wave Single Contra fast*, in four cases for *Wave Double slow* and in four cases for *Wave Double fast* (see Annex A). The mean number of slow activations exceeded the mean number of fast activations on both sides and in all drives. Opposite exceptions occurred five times in *Simple Contra*, five times in *Wave Single Contra* and once in *Wave Double* for the left hand as well as five times in *Simple Contra*, once in *Wave Single Contra* and once in *Wave Double* for the right hand. The standard deviations (Tab. 4.3) also indicated a wide variety of activations between participants.

Table 4.3: *Mean values and standard deviations for the number of activations in Simple Contra, Wave Single Contra and Wave Double, divided by speed and side.*

	Simple Contra				Wave Single Contra				Wave Double			
	Slow		Fast		Slow		Fast		Slow		Fast	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Mean	37	13	20	6	44	11	33	5	40	14	25	6
SD	19	7	23	6	17	8	30	6	21	9	23	6

Participants were asked if and how they experienced or noticed the systems activity. No participant reported any activity in the baseline drive. Fig. 4.10 shows the answers for the other three drives. All participants experienced tactile sensations in all drives (the answer also included the term haptic to account for different definitions known by subjects). Between five and seven subjects also heard the system in different drives while a total of three participants overall saw the system being active.

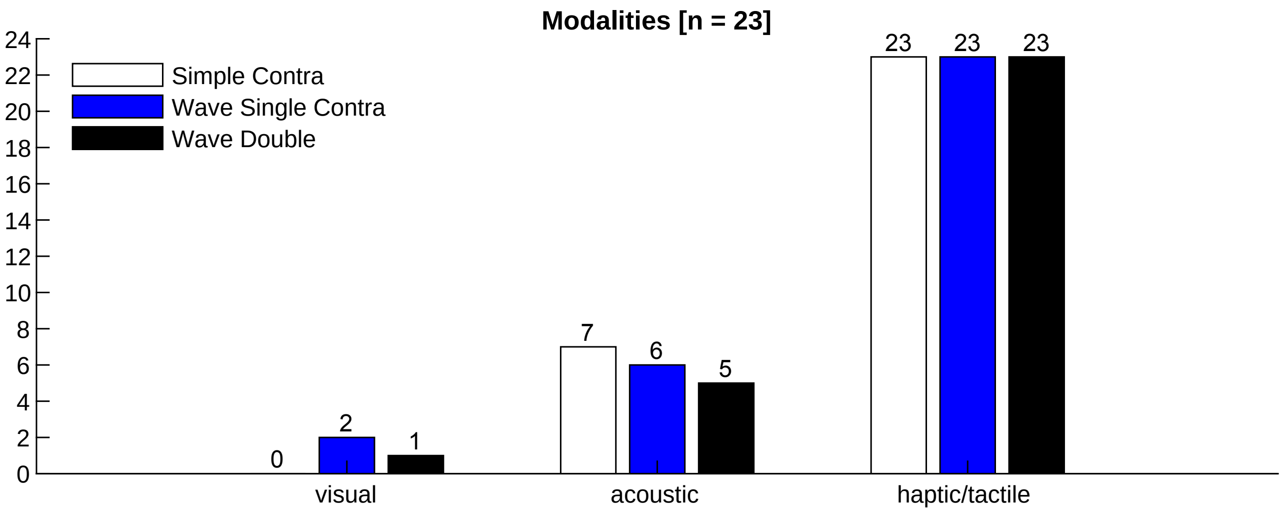


Figure 4.10: *Numbers of answers for the question how participants experienced or noticed the TWG systems activity.*

Fig. 4.11 shows the results from participants answers about the **function** of the TWG system as a lane keeping assistant. The correct answer would have been that the system was activated when the deviation from the lane center became too large and that it was always activated on the side of the deviation.Track *Wave Double* was an exception where the correct answer was that the system was always active on both sides at any sufficient deviation from the lane center. All subjects correctly identified the function of TWG as a lane keeping assistant in *Simple Contra* and *Wave Single Contra*. Seven participants described a concrete yet wrong function for *Wave Double* and one subject wasn't able to identify any function.

Participants gave unambiguous answers for the question on what **side** TWG was activated during the drives (Fig. 4.12). Subjects all identified the correct side/s in all drives. That included changing sides depending on the direction of deviation in *Simple Contra* and *Wave Single Contra*.

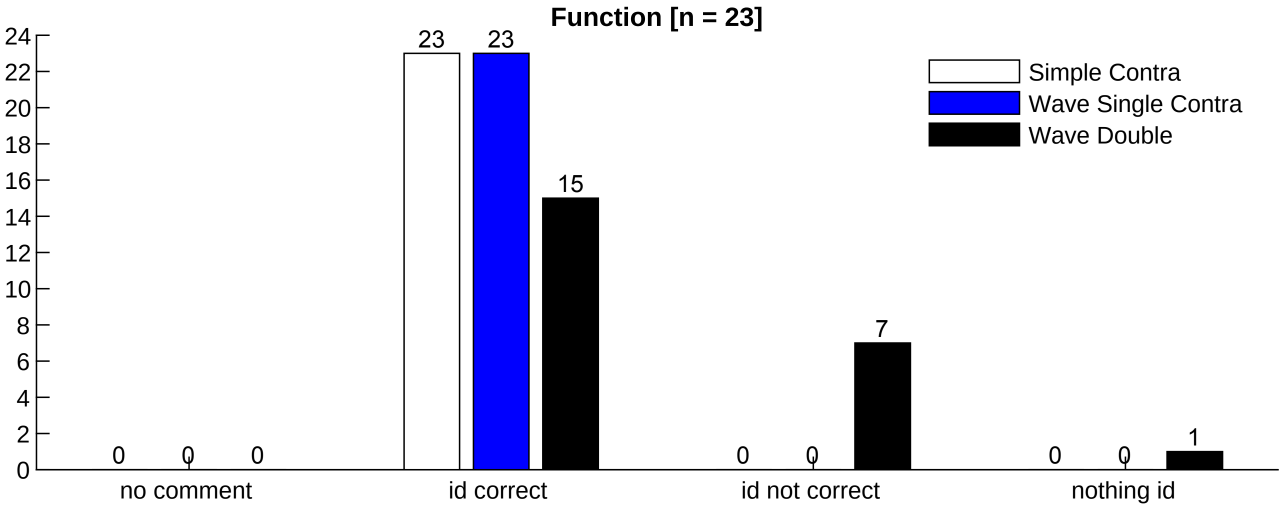


Figure 4.11: *Numbers of answers on the question of TWGs function as a lane assistant.*

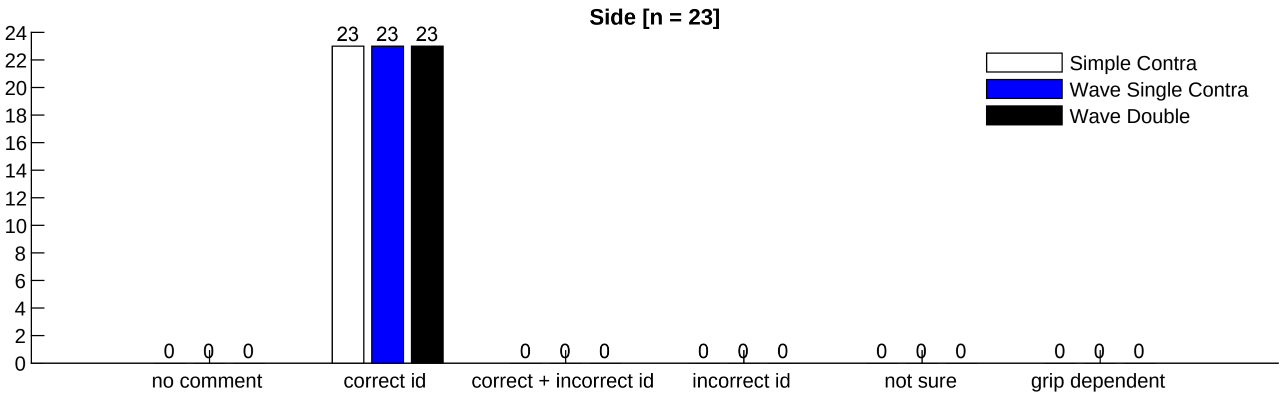


Figure 4.12: *Numbers of answers for the question on the side of TWG activations.*

Participants were not instructed that the entire second part of the study took place with the same power level of $24\ V/4.4\ W$. Still they were asked to evaluate the **power** of the solenoids activations. Results are shown in fig. 4.13. Seven answers were that the perception depended on the hands gripping position. Several participants reported changing power levels within a track: eight for *Simple Contra*, three for *Wave Single Contra* and seven for *Wave Double*. The majority of participants stated that the power level was appropriate with no further comment on changes between or within drives. No subject reported too little power while several answers indicated that the solenoids were overpowered. *Wave Single Contra* got the most answers for a good power level while receiving the least answers for overpowering or changing power levels within the drive.

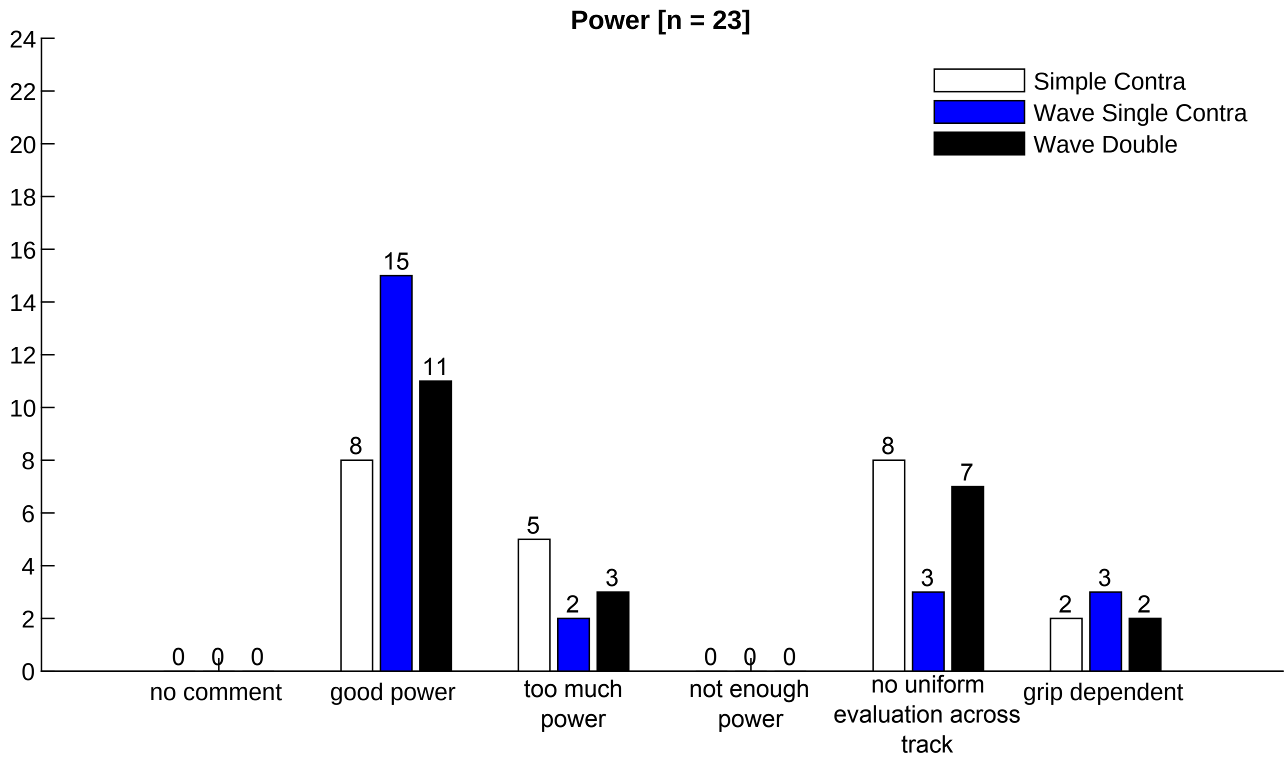


Figure 4.13: *Numbers of answers for the question on the power of TWG activations.*

There were two different **speeds** for the patterns. The majority of participants correctly identified the two step approach in *Simple Contra* and *Wave Single Contra* (Fig. 4.14). Most subjects could not identify the two different speeds in *Wave Double*. Eight answers overall stated they weren't sure about a change in speed.

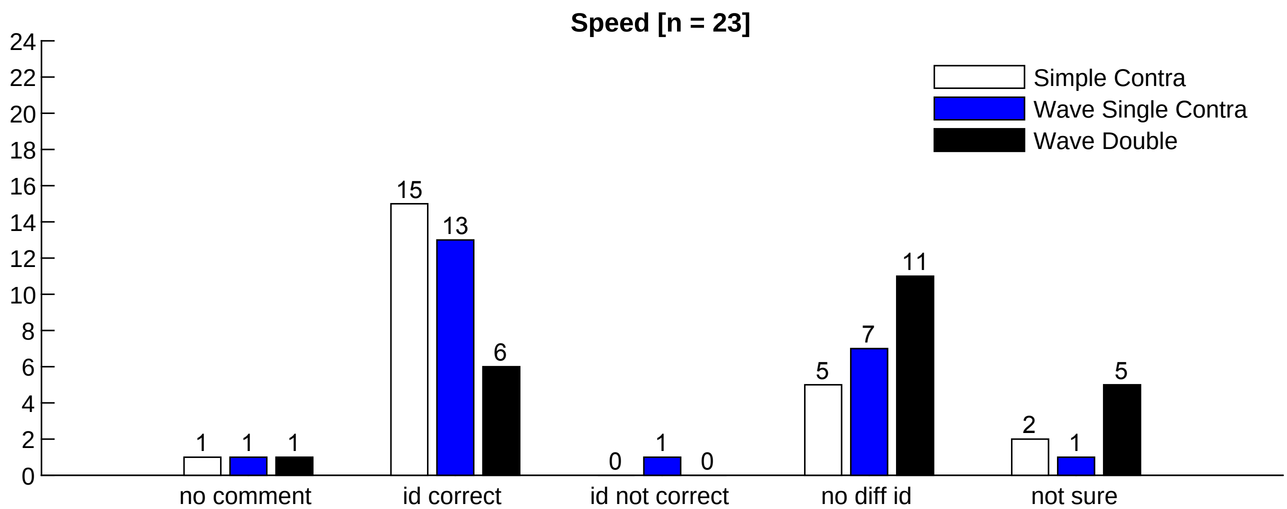


Figure 4.14: *Numbers of answers for the question on the speed of TWG activations.*

Results were more spread out for feedback on **pattern** identification. Fig. 4.15 displays answers for all drives except baseline where no pattern was active. Less than half of participants correctly identified the pattern for *Simple Contra* and *Wave Single Contra* while only four of 23 subjects gave a right answer for *Wave Double*. A similar number of subjects reported a recognized pattern although it was not the correct one. *Wave Double* had the most wrong pattern recognitions. Nearly a third of participants reported they thought there was a pattern but they were not able to identify it. One subject responded during *Simple Contra* that he only recognized random activations with no underlying pattern while a different one reported that there was no clear answer because perception differed depending on the hands gripping position.

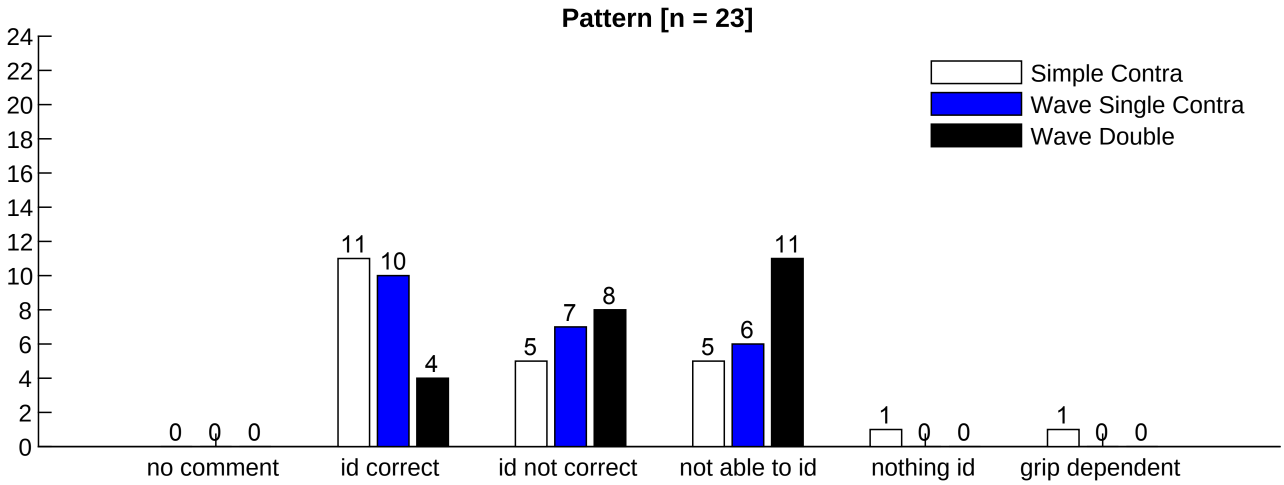


Figure 4.15: *Numbers of answers for the question on the pattern of TWG activations.*

4.1.3. Discussion of Study One

The first study had two focuses. The first part evaluated participants ability to perceive and distinguish separate power levels of TWG, because this was a recommendation from subjects of previous evaluations. The second part introduced TWG into a proper driving context for the first time. It evaluated participants ability to perceive and distinguish three different patterns of solenoid activations while using TWG as a normal steering wheel.

Participants could've been distracted from the study research goal or overwhelmed by TWG if they were very unfamiliar with lateral assistance systems as it is. Over 80 % of subjects reported to be at least somewhat familiar with this type of assistance. This means it's fair to assume their attention and experience with TWG was not tampered with by experiencing a whole new type of driving assistance for the first time in this study.

Higher power, i.e. $24\ V$, was expected to provide the best results because it should trigger the strongest perceptions. The number of correct answers (two points of contact) increased from $17.4\ \%$ at $12\ V$ to $30.4\ \%$ at $18\ V$ to $43.5\ \%$ at $24\ V$ on the left hand. The right hand also only saw a moderate increase from $8.7\ \%$ at $12\ V$ to $26.1\ \%$ at $18\ V$ to $30.4\ \%$ at $24\ V$. There are two possible reasons for this. First, the original plan was to adjust solenoid activations in part two individually for each participant. This would have depended on the individual gripping positions and what solenoids would be covered by the drivers hands as a result. It would have required some sort of visual inspection of the drivers hands before each test. Covid regulations prohibited the experimenter to be as close as necessary to the participant for a direct evaluation and a technical setup, i.e. cameras, was not feasible on short notice. This means there is no guarantee that participants had their hands at a correct position and some might have experienced a different number of contact points. The right hand faced away from the experimenter during tests, so there was no way, even from afar, to correct a subjects hand position. This could be an indication of the different results for the left and the right hand. Second, the two activated solenoids were spaced apart far above the spatial threshold of $10\ mm$ (Treede, 2011). Yet participants might have experienced phantom sensations (Hwang & Ryu, 2010). The two solenoids were triggered at the same time and, if both touched a subjects hand, they would then create the illusion of one combined touch in the spatial middle of both. The number of answers "one contact point" did not increase or decrease with power levels like the answer "two contact points" did. Answers were $26\ \%$ at $12\ V$, $34.8\ \%$ at $18\ V$ and $26\ \%$ at $24\ V$ for the left hand and $43.5\ \%$ at $12\ V$, $56.5\ \%$ at $18\ V$ and $52.2\ \%$ at $24\ V$.

Subjects also rated how confident they were with their answers on a likert scale from 1 very uncertain to 5 very certain. This helped to put the number of correct and incorrect answers into perspective. In half of the six cases (two hands x three power levels) the correct answer "two contact points" was rated with the lowest certainty. Fig. 4.8 shows a tendency for answers with less contact points to be rated with higher confidence. High confidence in wrong answers also points towards no future use of patterns with simultaneous activations, at least if they are supposed to represent a pattern that should to be distinguishable from a single touch for example.

Part two revealed one more important fact regarding different power levels. Power was repeatedly an issue mentioned by subjects of prior evaluations during the iterative construction of TWG. Answers of "no contact point" decreased from $43.5\ \%$ at $12\ V$ to $4.3\ \%$ at $18\ V$ and $8.7\ \%$ at $24\ V$ on the left hand. Subjects reported no contact at all in $43.5\ \%$ of cases for $12\ V$ and $0\ \%$ for $18\ V$ and $24\ V$.

Increased power seems to help greatly with overall perception, although the specific test with two simultaneous points of contact had flaws considering the experimental setup and the phenomenon of sensory saltation. Future tests with TWG should be carried out with the maximum power level of $24\ V$ with regard to proper perception. Patterns should not include simultaneous touches even if they are further apart than the spatial two-point threshold.

Analysis of the third study part showed three issues with the number of activations for each participant (Fig. 4.9). **First**, the key problem overall was that participants experienced a different number of activations. Adding up all activations for each participant resulted in a range from 68 to 513 total activations per subject. Multiplied with the durations of each speed that translated to a range from $3,175\ ms$ to $20,955\ ms$. Participants with more activations had much more time to experience and evaluate the system and its properties, in the most extreme case more than six times more time. An improved evaluation of the TWG system required a limited and equal time span for each participant to experience and evaluate the TWG system.

Second, the number of activations on the left side exceeded the activations on the right side. This was due to the simplified simulation setup. Drivers sit to the left of the vehicles lateral center in right hand traffic. Participants were trained from everyday driving for a driving style that accounted for the offset.

They most likely adjusted their point of view in the simulation to be to the left of the lane center - the point of view they would have when driving a regular vehicle in the center of the lane. Subjects were positioned in the center of their simulated vehicle though, like in a Go-Kart. Even though participants were instructed about this, it appears that their regular driving habits overpowered the one time instruction. This lead to the simulated vehicle to always drive too far left in the lane, which made it much easier to cross the left boundary and activate TWG on the left side. An improved evaluation of the property "side" of the TWG system required a fool proof and balanced study design that eliminated the chance for one side to be activated much more often than the other.

Third, the mean number of slow activations exceeded the fast ones. This was due to the design of the lane keeping assistance. A fast activation was only possible if the COG moved through the area of slow activations first. So there was at least one slow activation for each fast activation. On the other hand, slow activations were possible without reaching fast activations if the COG stayed within the corresponding area or moved back into the dead-band in the middle. The participants that had more fast than slow activations remained in the corresponding "fast area" longer than they needed to pass through the slow activation area. An improved evaluation of the property "speed" of the TWG system required a different usage of the system as well as an adapted study design that balanced both speeds better.

The widespread number of activations did not warrant a solid basis for a statistical analysis and comparison of drives or patterns. So study one was only analyzed with respect to overall tendencies, as an evaluation step of TWG and as a preparation for study two.

Subjects answers were as expected regarding the **modalities** through which they experienced TWGs activities. A relatively small number of participants also heard the system despite wearing noise cancelling head phones and listening to static white noise (Fig. 4.10). It was still a major improvement from every subject hearing the system without any hearing protection. Visual perception of TWGs perception was not actively prevented although concentration on the simulation screen should've steered glances away sufficiently from TWG. A total of only three subjects over all drives can most likely be attributed to chance rather than to active exploring by participants to gather information.

It was expected that participants would have no trouble identifying the basic **function** of TWG as a lane keeping assistant. Yet the deviating results for *Wave Double* were a first indication that this pattern created some problems for subjects. TWG was never intended to be used as a mere lane keeping assistant, so the results for correct identifications of the function didn't carry much weight for the ongoing construction and evaluation process. Participants feedback was still helpful because it showed that subjects were able to make a logical connection between TWG activations and a driving situation.

Subjects answers on the **side** of activation gave good feedback that the activations from one side didn't resonate on the other side. This was reported as a problem in other studies that used vibration motors (see Hwang and Ryu (2010); D. Kern et al. (2009)). This result goes two ways: Participants didn't perceive or at least interpret passive activities originating from the other active side on a non activated site as intentional activations. In addition, subjects didn't interpret intentional activations on both sides in *Wave Double* as one real activation on one side and one passive resonation on the other side, but as two intentional activations on each side.

Previous evaluations had already indicated that the highest **power** level would fit TWGs use the best. That's why the third study part was conducted with $24\ V/4.4\ W$ only. Despite mixed feedback, 15 out of 23 participants rated the power level as good in the *Wave Single Contra* drive. This was the only category where *Wave Single Contra* got almost twice as many answers as *Simple Contra* for good and appropriate power. *Wave Single Contra* also got the least answer that participants perceived changing power levels within the drive.

The **speed** property, of more precisely t_{delay}, didn't contribute to clear perception. The values of $50\ ms$ and $35\ ms$ were much lower than $180\ ms$ and $80\ ms$ in earlier evaluations. After these two attempts with fixed delays for all subjects, a different approach for the final study was to use delay parameters on a per-subject-basis, meaning each participant requires their own set of t_{delay} to properly recognize differences.

Participants gave more interesting answers for the questions on power and speed. Fourteen of 69 answers (three patterns x 23 participants) stated that they noticed a two step difference, but described it as a different *intensity* because they weren't certain whether it was a different speed, a different power or both (six for *Wave Double*, seven for *Simple Contra* and one for *Wave Single Contra*). It was enough for TWGs evaluation that subjects could differ between two different levels but these answers indicated that different power and speeds my not be handled as separate properties in the future.

Pattern recognition was the most important question for the third part of the study. While the evaluations in chapters 3.1.4 & 3.2 showed very good recognition of *Wave Single Contra*, this pattern was identified much worse in this study. With changes in power, speed and the overall usage of TWG it wasn't clear what parameter exactly led to this change. The mixed results in this study also offer no clear favorite pattern on first sight. It appears the best recognizable pattern is dependent on a combination of all tested properties in this study. *Wave Double* was repeatedly evaluated worst, i.e. least correct identifications of function and pattern. *Wave Double* was also the pattern where most subjects couldn't recognize different speed levels. It is possible that this was based on the number of active pins at the same time which Shakeri, Brewster, et al. (2016) found out can influence perception when it becomes too many. Shakeri, Brewster, et al. (2016) also recommended to apply tactile patterns only on one hand to not overwhelm drivers. This study supports that statement. Participants rated *Simple Contra* and *Wave Single Contra* similar but with nuances of differences. *Wave Single Contra* was rated better and more clearly than *Simple Contra* in power perception, while merely one participant more identified the pattern *Simple Contra* than the pattern *Wave Single Contra*. Yet another, more detailed evaluation would have been necessary to determine a clear favorite.

Wave Single Contra was chosen as the only pattern to continue TWGs overall investigation with for organizational reasons, because no further study could be undertaken solely for the construction evaluation.

It also combined good results from this study and it incorporated a distinct feature, that binary vibration systems and *Simple Contra* didn't have, i.e. spatio-temporal encoding: the wave.

4.2. Study Two - Haptic Shared Control with TWG

The goal of this second study was to gain insight on performance increase or decrease when combining TWG with conventional HSC, as explained in chapter 1. The study used the same physical prototype as the first study. The pattern *Wave Single Contra* was taken over from the first study for all TWG activations. Borojeni et al. (2017) reported a lack of force as a flaw of their study design. In addition to the results from study one, this meant that study two only used the highest power level available: $24\ V\ /\ 4.4\ W$.

4.2.1. Study Two Setup

Physical setup

The study was conducted in a driving simulator called "Sitzkiste 2" at the chair of ergonomics at TUM in July and August 2021 (Fig. 4.16). Covid-19 regulations and safety measurements were applied. A single participant sat in the driving simulator while the experimenter sat at a separate tables approximately two meters away. The experimenters table was equipped with different computers and displays to control the experiment. The driving simulator consisted of a base plate mounted on four linear actuators that can simulate yaw and pitch motions. The simulation environment was displayed on five 50 inch 4K resolution TVs that were positioned in a half circle in front of the participant. The regular steering wheel was removed and replaced with the TWG system. Rotation of the steering wheel could be controlled by an electrical motor (SENSO-Wheel SD-LC by Sensodrive GmbH). Participants sat on a regular car seat that was only adjustable longways. No other adjustments were possible. The simulator was equipped with three pedals that were not used in this study. Participants had to wear noise cancelling headphones (Bose QuietComfort 35) that played static white noise during all active phases of the experiment. The headphones could be taken off in intervals, i.e. changing to the next experiment phase or during questions.

Participants were only allowed to touch surfaces that were absolutely necessary for the experiment. That included the TWG system, the seat and other parts necessary to climb into the seat. All questionnaires were filled in an interview style by the experimenter who read questions out loud and wrote down answers at his table. All surfaces were disinfected between participants. Participants could decide individually to take off their protective face mask while the experimenter wore his during the entire experiment. The TUM ethics committee raised no objection to this study. All participants signed informed consent forms. Questions and answers were documented using LimeSurvey. SILAB 6.0 was used as driving simulator software. The connection between SILAB and the Arduino micro controller activated and deactivated the TWG system.

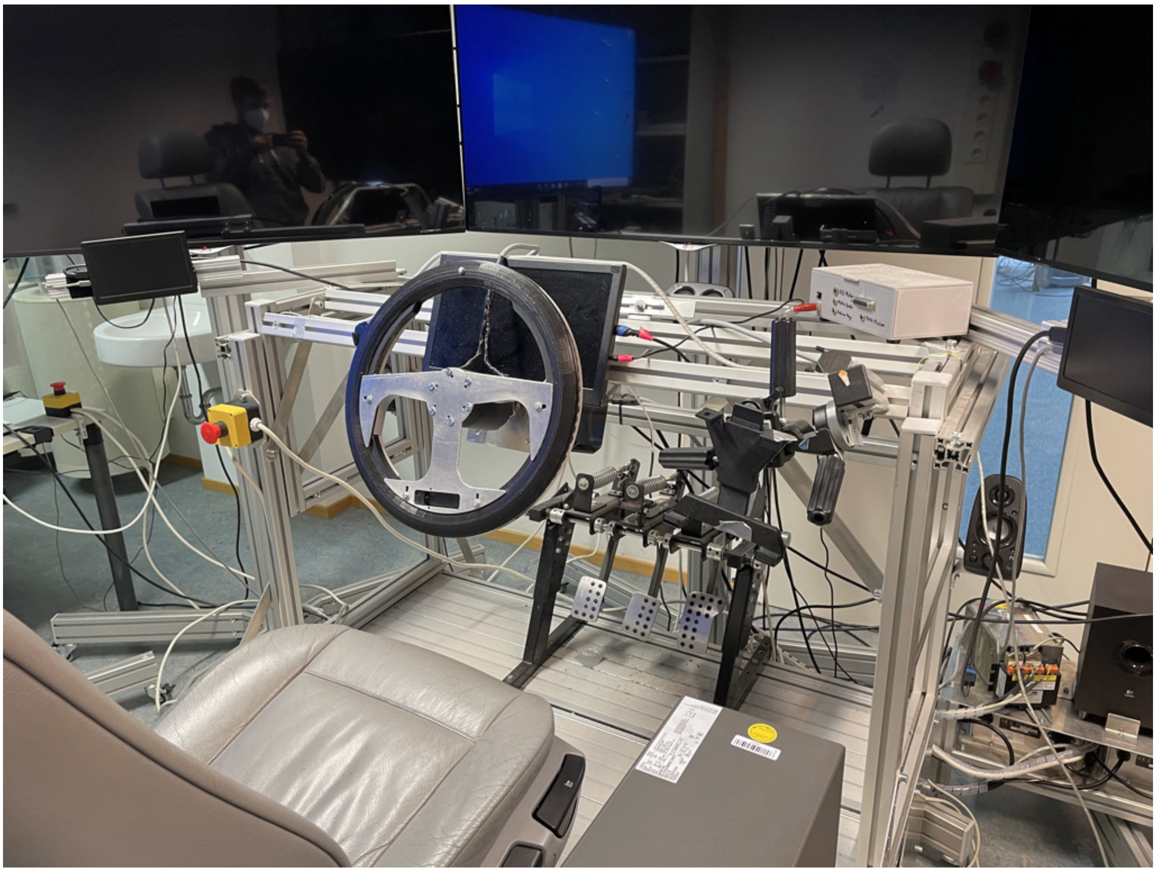


Figure 4.16: *Driving simulator "Sitzkiste 2" at the chair of ergonomics at TUM. TWG, the seat and three out of five TV screens are visible.*

Procedure

There were three separate parts of the experiment that each participant went through The **first part** was formalities and a first demographic questionnaire. Participants generated an individual pseudonym to name their data. Demographics included age and gender as well as prior experience with lane keeping driver assistance.

The goal of the **second part** was to identify a range for the delay parameter for TWG activations for each participant individually. This differed from the first study, where every subject experienced fixed delays of $50\ ms$ and $35\ ms$. The tests included several activations of the pattern *Wave Single Contra* to find the lowest delay (equals fastest speed) at which the subject could identify the wave pattern.

Subjects were informed that they would be randomly presented with one of three patterns: *Wave Single Contra* from bottom to top like in the first study, *Wave Single Ipsi* from top to bottom or altogether *random* activations of solenoids. It was their only task to identify which of those three patterns was played. Participants were not informed that every pattern would be *Wave Single Contra* from bottom to top and that the real goal of this part was to find a suitable delay parameter.

Subjects placed their left hand on the steering wheel, put on noise canceling headphones playing white noise like in study one, and closed their eyes. They were then presented with the first wave (from bottom to top) in the form of three repetitions with $t_{delay} = 30\ ms$. Three repetitions were used because other studies (Enriquez et al., 2001; D. Kern et al., 2009) reported that repeating patterns helped participants to confirm their initial judgements. Subjects then reported which of the three supposedly possible patterns they perceived and how sure they were about their judgment on a scale from 1 = very unsure to five = very sure. If they identified *Wave Single Contra* from bottom to top with a certainty of at least four, the test run was finished. The test continued with a delay parameter that was increased by $10\ ms$ if they reported a wrong pattern or a lower certainty. This process continued to a maximum of $200\ ms$ or until subjects answered correctly.

The next run had subjects switch to the right hand and experience the former test procedure this time going downwards in $10\ ms$ steps from $t_{delay} = 200\ ms$ to the minimum of $t_{delay} = 30\ ms$. Participants then went back to the left hand again and went through the process with $10\ ms$ steps from $t_{delay} = 200\ ms$ down to the minimum of $t_{delay} = 30\ ms$. Finally they switched back to the right hand and went through the process with 10 ms steps from $t_{delay} = 30\ ms$ upwards to the maximum of $t_{delay} = 200\ ms$. The experimenter chose one single delay parameter for the rest of the study for each subject individually based on their answers in these four test runs.

The **third part** consisted of three drives in an identical simulation environment. Each drive had 15 scenarios with identical setups back to back with no interruptions. The task for participants was to steer the vehicle through one of seven possible portals with only one being the correct one in each scenario (Fig. 4.17 & 4.18). Longitudinal speed was fixed at $40 km/h$. The vehicle accelerated automatically to that speed at the very beginning of the track and kept it constant throughout the entire drive.

Figure 4.17: *Driving scenario that appeared 15 times in a row with no interruptions during each of the three drives in study two. This view is adjusted for presentation purposes, subjects point of view in the simulation was positioned at a regular height for a driver in the driver seat.*

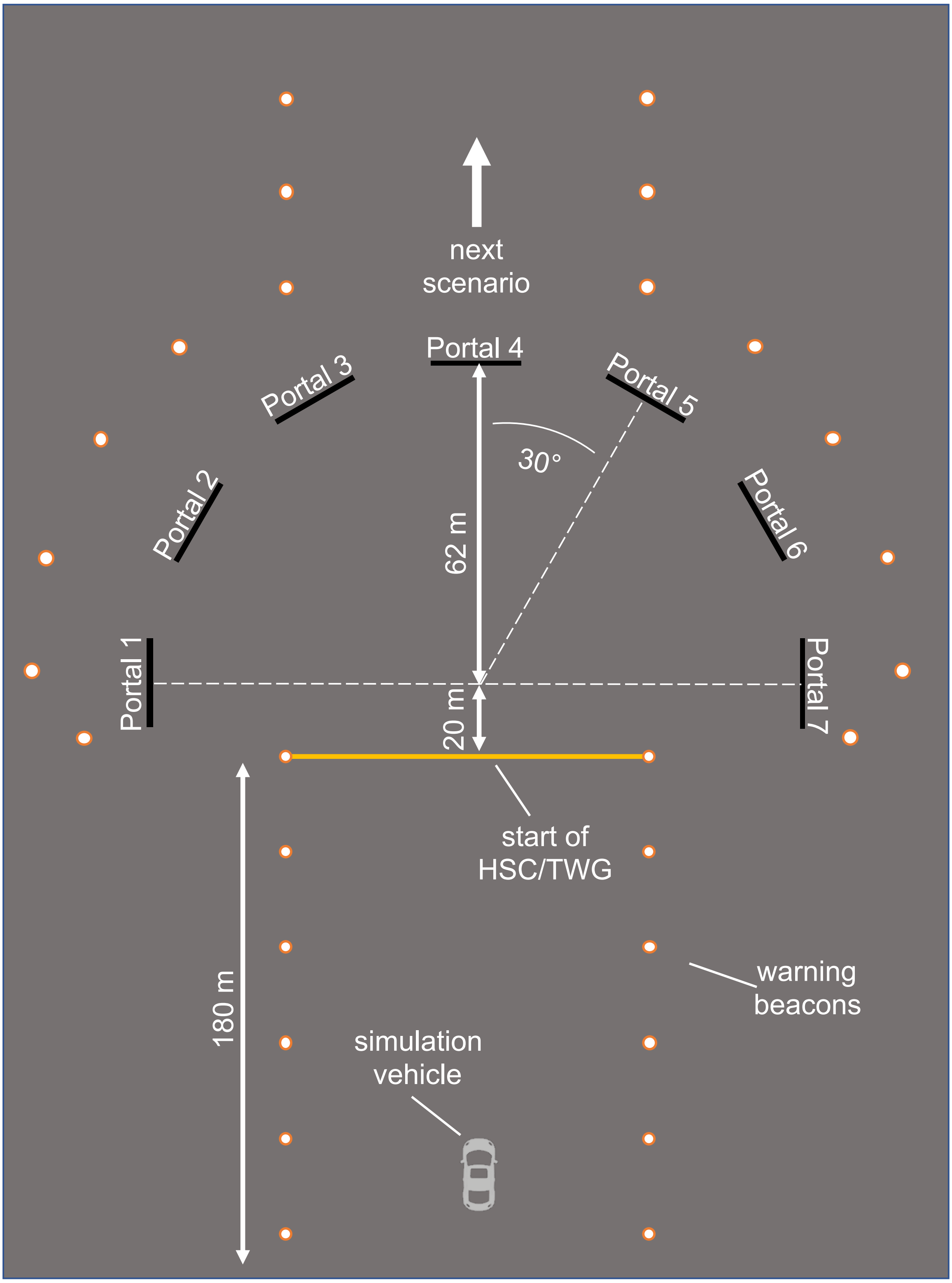


Figure 4.18: *Simplified schematic of a scenario from a birds eye view. Warning beacons always limit the possible driving area of the otherwise endless asphalt surface. Special indications are for the starting point of the simulation vehicle, the visible orange lane that starts the three second activity of HSC and/or TWG, the portals and the beginning of the following scenario. Elements not to scale.*

Each scenario began with a straight drive through a $180\ m$ long passage that was aligned with warning beacons left and right (Fig. 4.17). It was possible for subjects to drive more to the left or the right in this passage but at that point they were still unaware which portal would be the right one. So all subjects followed the recommendation to drive as much in the middle as possible to have an even distance to all possible portals. Information on the correct portal was communicated once the COG of the simulation vehicle crossed the line between the last two beacons (Fig. 4.18):

1. **TWG only:** TWG was active for exactly three seconds. The speed and side of the wave depended on the deviation angle α between the longitudinal axis of the simulation vehicle and the imaginary line from the vehicles COG to the center of the correct portal (Fig. 4.19). A larger angle meant a faster speed. An angle of $60°$ or higher equaled the minimum value for t_{delay} (fastest speed) determined in the second part of the study. An angle of $0°$ equaled the minimum value plus $200\ ms$, resulting in the maximum for t_{delay} (slowest speed).

2. **HSC only:** Torque was applied to the steering wheel column for exactly three seconds. The value and direction of the torque depended on the angle between the longitudinal axis of the simulation vehicle and the imaginary line from the vehicles COG to the center of the correct portal (Fig. 4.19). A larger angle meant a higher torque. The torque was limited to ±$1.5\ Nm$ for safety reasons (see chapter 2.3). An angle of $0°$ equaled $100\ mNm$ while an angle of $30°$ or larger equaled $1.5\ Nm$. Torque was not zero at $0°$ to create comparable conditions with TWG only where a wave with a very low speed was active even at $0°$.

3. **HSC and TWG:** Both systems were active for exactly three seconds with the same configurations as in their single drives.

HSC was mapped to a smaller angle area than TWG due to its twofold assistance. HSC has to provide as much torque as possible in a limited time and with a saturation limit for active steering assistance. The angle where torque is capped should be as low as possible so that the maximum torque is reached as soon as possible. This enables HSC to apply the most effect on active steering. On the other hand, a low torque cap minimizes the resolution of torque that drivers can sense and distinguish. Assistance becomes almost binary with only extreme values or zero torque. The torque cap should be set as high as possible for HSCs information quality. An angle of 30° was appropriate for the configurations of the scenario in this study. In comparison, TWG only has to fulfill the part of information assistance because it doesn't interfere with the active steering task. This enables TWG to provide a bigger resolution by setting the highest assistance to a larger angle than HSC.

The hypothesis for this study is that TWG could benefit from the lack of a safety limit like torque. This saturation limit was easily reached with portals one, two, six and seven. This is why each drive included the four outer portals as the correct one three times each. The remaining three portals in the middle were the correct one in one scenario each. The order of correct portals was randomized across drives and participants. Different portals were chosen as driving "goals" because they represented clearly different trajectories that had to be driven to reach them.

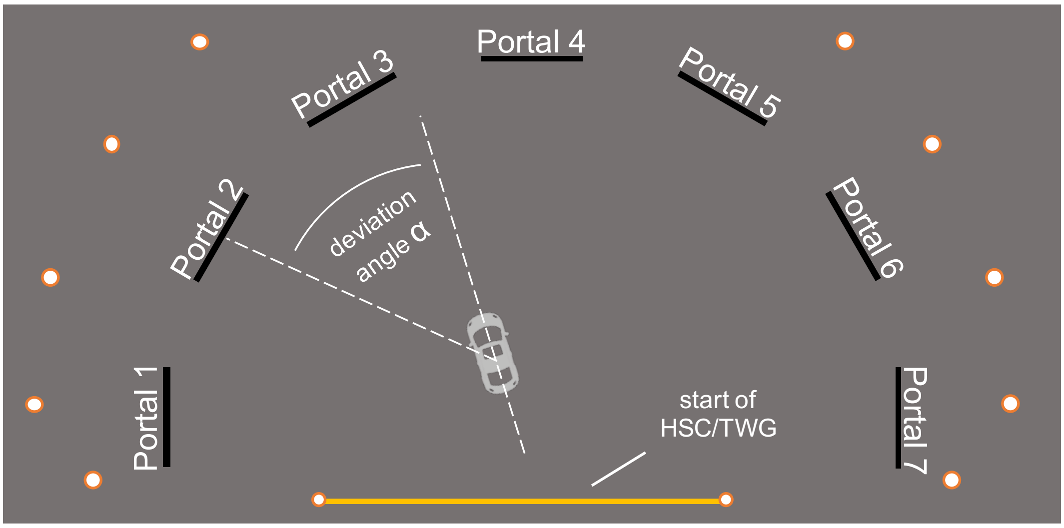


Figure 4.19: *The deviation angle α was defined by the longitudinal axis of the simulation vehicle and the invisible direct connection between the vehicles COG and the center of the correct portal. Angles were maximum 180° before switching sign to negative values between -180° and 0° and changing direction of HSC and TWG.*

Planned analysis

Analysis was carried out using MATLAB 2022a (Mathworks Inc.) and JASP v0.16.2 (University of Amsterdam). Statistical analysis in the form of a paired t-test was applied to check the following hypothesis:

H_1: The condition TWG & torque leads to less missed portals than the condition torque-only.

4.2.2. Results of Study Two

Part one

Eight female and seven male subjects participated in the study. The mean age was 28.7 years with a standard deviation of 2.2 years. All participants completed all parts of the experiment. Participants were moderately familiar with lateral assistance systems as 60% rated their prior experience with at least 1 on a scale from -3 to +3 (Fig. 4.20). One participant gave no answer on that question.

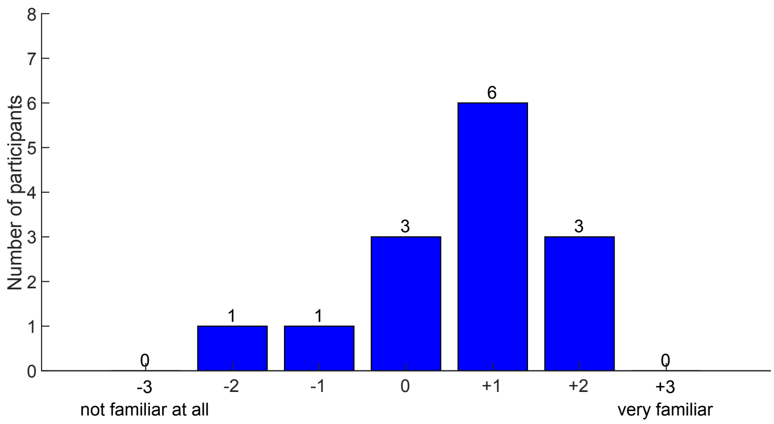


Figure 4.20: *Participants prior experience with lateral assistance systems in study two.*

Part two

Fig. 4.21 shows the distribution of delay parameters t_{delay} determined in the second part of this study. The minimum parameters are distributed across eight different values with their respective maximum counterparts all being set $200\ ms$ higher. The chosen values range from the minimum possible $30\ ms$ to $120\ ms$.

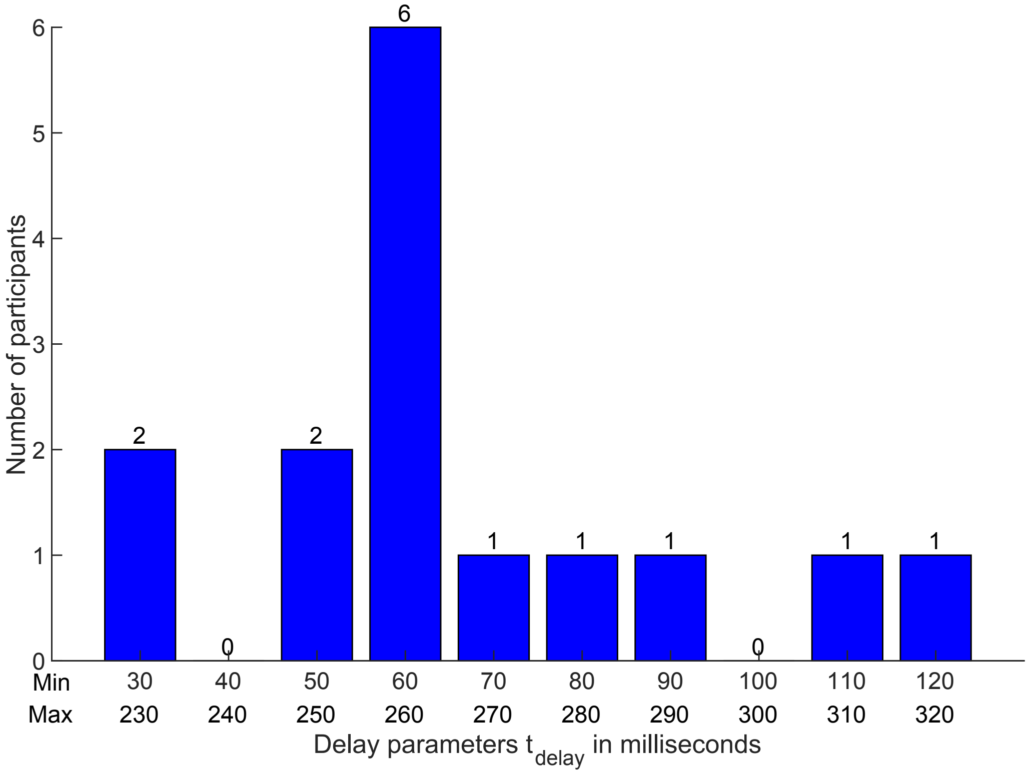


Figure 4.21: *Chosen delay parameters t_{delay} (minimum and maximum) by participants in study two.*

Part three - Planned analysis

There were 180 potential scenarios to analyze per condition: three for each of portals one, two, six and seven for 15 subjects. One scenario had to be taken out of the analysis for the torque-only and the TWG & torque condition due to a faulty configuration of a drive with a correct portal two. Two scenarios had to be taken out of the analysis for the TWG-only condition, one with a correct portal one and one with a correct portal two. This leaves 179 scenarios for torque-only and TWG & torque and 178 for TWG-only.

Figures 4.24, 4.25 and 4.26 show the course of deviation angles α, torques and TWGs delay parameters t_{delay} during the three second activation time. Table 4.4 shows how long the torque and the delay parameter t_{delay} were saturated at their limits in all three conditions.

Participants had to steer their vehicle through the only correct portal in each scenario. Fig. 4.22 shows the number of correct and incorrect choices for the four outmost portals. Portal one and two were missed in the TWG-only drive the most in comparison to the other two drives. The smallest number of misses

Table 4.4: *Times torques and delay parameters t_{delay} were saturated in all three conditions of study two. $^{\dagger}t_{delay}$ was not saturated at the onset of activation. Instead, times until the absolute t_{delay} value decreased for the first time are used.*

	Torque at saturation level	**TWG at minimum t_{delay}**
	Mean (SD)	Mean (SD)
TWG-only Portals two & six	–	1098 ms† (301 ms†)
TWG-only Portals one & seven	–	1592 ms (333 ms)
Torque-only Portals two & six	1572 ms (367 ms)	–
Torque-only Portals one & seven	2573 ms (308 ms)	–
TWG&torque Portals two & six	1637 ms (309 ms)	453 ms† (79 ms†)
TWG&torque Portals one & seven	2652 ms (270 ms)	1620 ms (330 ms)

happened for portal one in the torque-only drive and for portal seven in the TWG&torque drive. All four portals combined, the correct portal was missed 44 times in the torque-only drive (~$25\ \%$), 68 times in the TWG-only drive (~$38\ \%$) and 42 times in the TWG & torque drive (~$23\ \%$).

On average, participants did not miss less portals in the condition TWG & torque (M = 2.9 , SD = 2.0) than in the condition torque-only (M = 2.9, SD = 1.9). This difference was not significant $t(14) = 0.0$, $p = .5$ with no effect $d = 0.0$. The results do not support the hypothesis H_1.

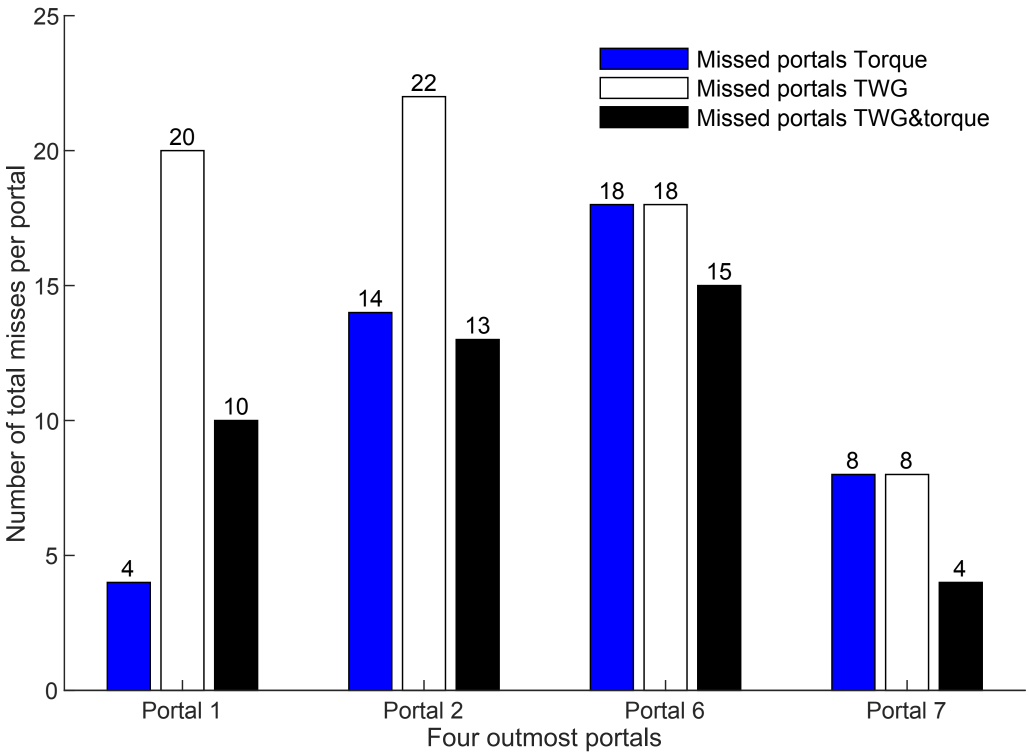


Figure 4.22: *Number of missed portals for the four outmost portals across all participants and drives.*

Part three - Explorative analysis

Fig. 4.23 shows the trajectories for all drives with the correct portals one & seven (red) and two & six (black). Table 4.5 shows how many meters on the lateral axis each drive covered within the three second window and how much the yaw angle changed. The average difference of covered lateral distance between portals one & seven and portals two & six was larger in the TWG-only condition compared to torque-only and TWG&torque. The condition had a significant effect on the calculated differences, $F(2, 42) = 46.611$, $p < .001$, $\omega^2 = .670$ with a large effect. ω^2 can have values between -1 and +1 with 0 standing for no effect. Post-hoc tests with Bonferroni correction showed a significant difference between torque-only and TWG-only ($t = 7.539$, $p < .001$, $d = 2.753$) with a large effect as well as a significant difference between TWG&torque and TWG-only ($t = 8.994$, $p < .001$, $d = 3.284$) with a large effect. Cohens d starts at .8 for large effects.

The same effect was present for the average difference of changes in yaw angles between portals one & seven and portals two & six. The condition had a significant effect, $F(2, 42) = 15.981$, $p < .001$, $\omega^2 = .400$ with a large effect. Post-hoc tests with Bonferroni correction showed a significant difference between torque-only and TWG-only ($t = 5.308$, $p < .001$, $d = 1.938$) with a large effect as well as a significant difference between TWG&torque and TWG-only ($t = 4.339$, $p < .001$, $d = 1.584$) with a large effect.

Table 4.5: *Lateral distances covered and changes in yaw angles for the three conditions torque-only, TWG-only and TWG&torque.*

		Lateral distance covered	**Change in yaw angle**
		Mean (SD)	Mean (SD)
	Portals one & seven	15.1 m (2.2 m)	77.5° (13.2°)
Torque-only	Portals two & six	15.0 m (2.2 m)	69.9° (11.0°)
	Difference	0.17 m (0.41 m)	7.67° (4.10°)
	Portals one & seven	9.7 m (2.6 m)	54.0° (13.7°)
TWG-only	Portals two & six	6.5 m (2.3 m)	35.0° (10.9°)
	Difference	3.16 m (1.25 m)	18.70° (7.16°)
	Portals one & seven	14.9 m (1.7 m)	75.3° (10.9°)
TWG&torque	Portals two & six	14.3 m (1.9 m)	65.6° (9.7°)
	Difference	0.65 m (0.87 m)	9.68° (5.40°)

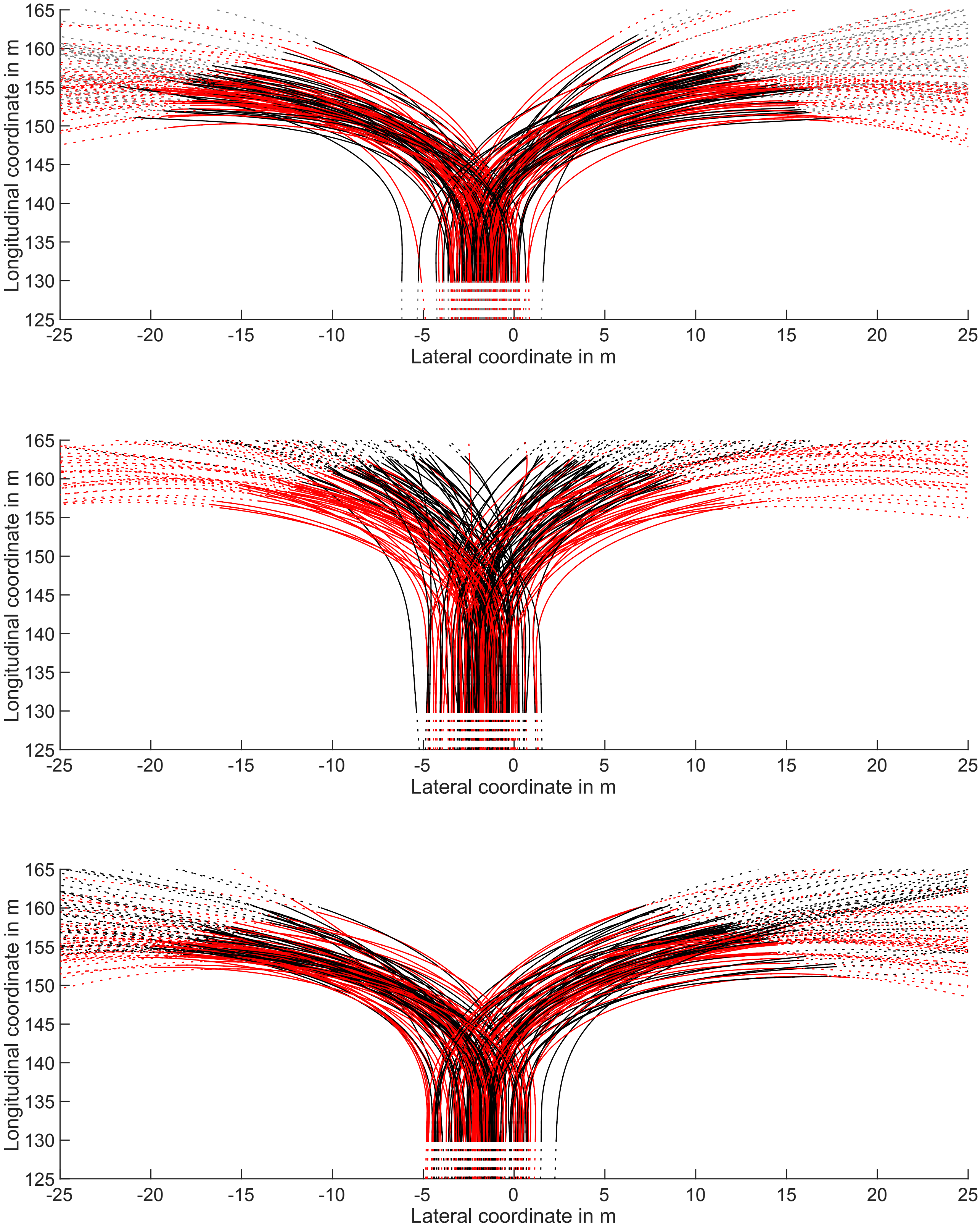


Figure 4.23: *Trajectories for the three second assistance in Torque-only (top), TWG-only (middle) and TWG&torque (bottom). Dotted lines indicate times where no assistance was active yet/anymore, filled lines indicate times when assistance was active. Red lines are trajectories with correct portals one & seven, black lines are trajectories with correct portals two & six.*

Fig. 4.24 shows the course and values of the applied torque in the corresponding **torque-only** drives. Black lines represent the drives where portals two and six were correct. Red lines represent the drives where portal one and seven were correct. The deviation angle α was smaller for portals two and six at the assistance onset which is why the assistance torque declines from the saturation of $\pm$1500 mNm earlier then for the drives with correct portals one and seven. The torque switched sign on average 5.7 times (SD: 2.5) per drive (one drive including twelve scenarios relevant for analysis), which represents the times drivers had to switch the steering direction. Torque didn't switch sign at all in 95 out of 179 scenarios (~$53\ \%$). Ten out of 179 scenarios (~$6\ \%$) used the saturated limit of $\pm 1500\ mNm$ continuously until the end of the three seconds activation, all in drives with correct portals two or six. Nine out of 179 scenarios (~$5\ \%$) reached both saturation levels of $+1500\ mNm$ and $-1500\ mNm$ at least once in the same scenario.

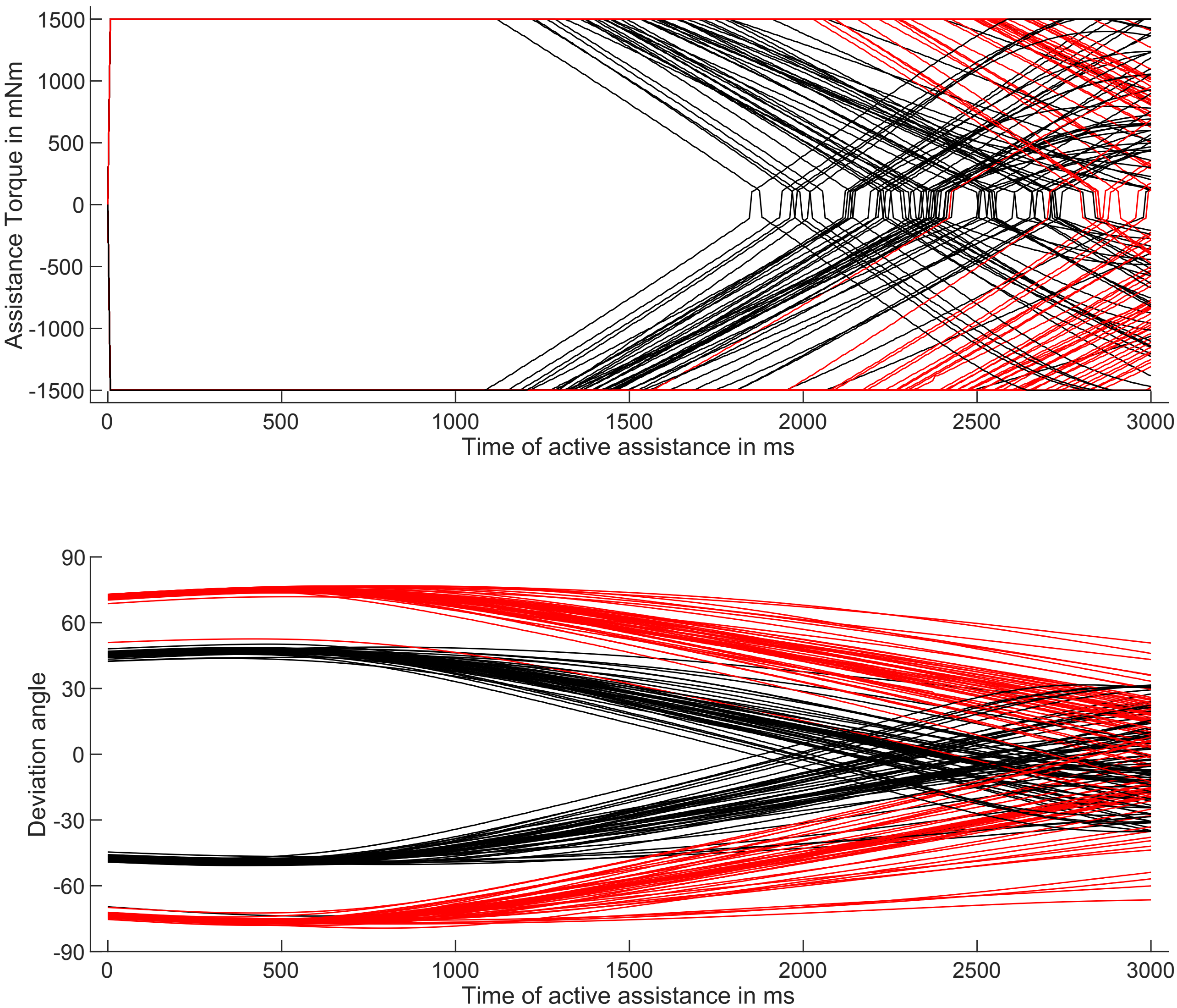


Figure 4.24: *Course of the assistance torque and the deviation angles for the four outmost portals in the torque-only drives. Drives for portals one & seven are shown in red, portals two & six in black. Positive and negative values result from clockwise and counter clockwise rotations. The area around 0 mNm ist skipped because of the minimal value of* $\pm$*100 mNm.*

Fig. 4.25 shows the qualitative course of the TWG delay parameters in the corresponding **TWG-only** drives. Black lines represent the drives where portal two and six were correct. Red lines represent the drives where portal one and seven were correct. The deviation angle α was larger for portals one and seven at the assistance onset which is why these drives used the minimum delay parameter t_{delay} longer than/at all compared to the drives with correct portals two and six. The pattern never switched sides in any of the 178 scenarios, which means drivers never needed to be informed to switch their steering direction. This seems extreme on first sight, yet it is supported by data from the underlying deviation angle. Fig. 4.25 shows all deviation angles converging towards $0°$ yet none reaches or crosses the value within the three second time frame. Ten out of 178 scenarios (~$6\ \%$) used the minimum delay parameter continuously until the end of the three seconds activation. Fig. 4.25 also includes five drives where subjects failed to interpret TWGs pattern, which is why the deviation angles diverge away from the expected zero degrees. These results are still included in the analysis.

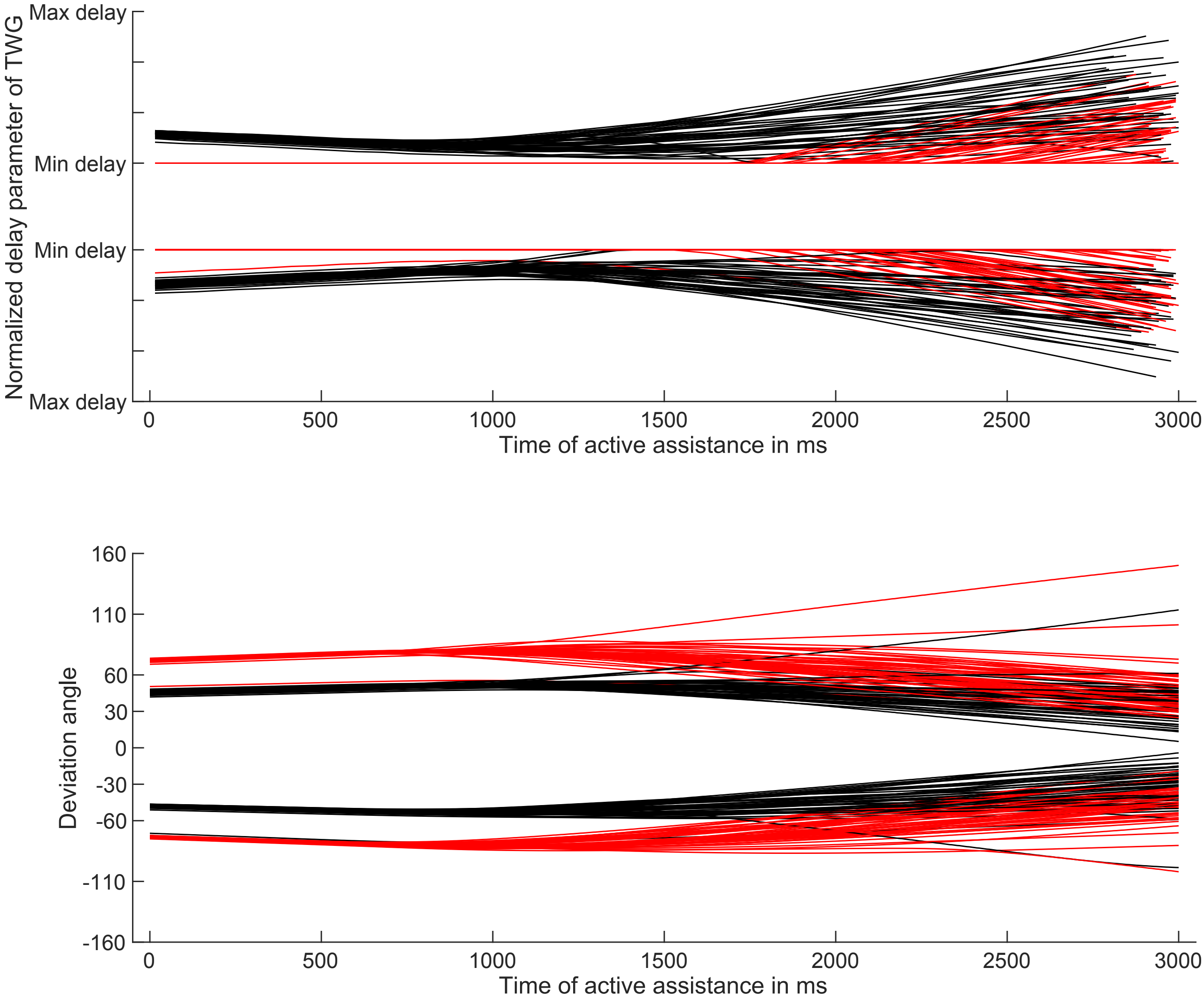


Figure 4.25: *Illustrative course of t_{delay} and α for the four outmost portals. Drives for portals one & seven are shown in red, portals two & six in black. Upper and lower lines result from clockwise and counter clockwise rotations. The area in the middle is empty because of a minimal delay parameter $\geq$ 30 ms and no zero crossings at all for all participants. All delay parameters are shown normalized for one minimal and maximal value. Actual courses of delay parameters are equal in quality but differ in quantitative value.*

Fig. 4.26 shows the courses for torque, delay parameters and deviation angles for the drives with both TWG and torque. Black lines represent the drives where portals two and six were correct.

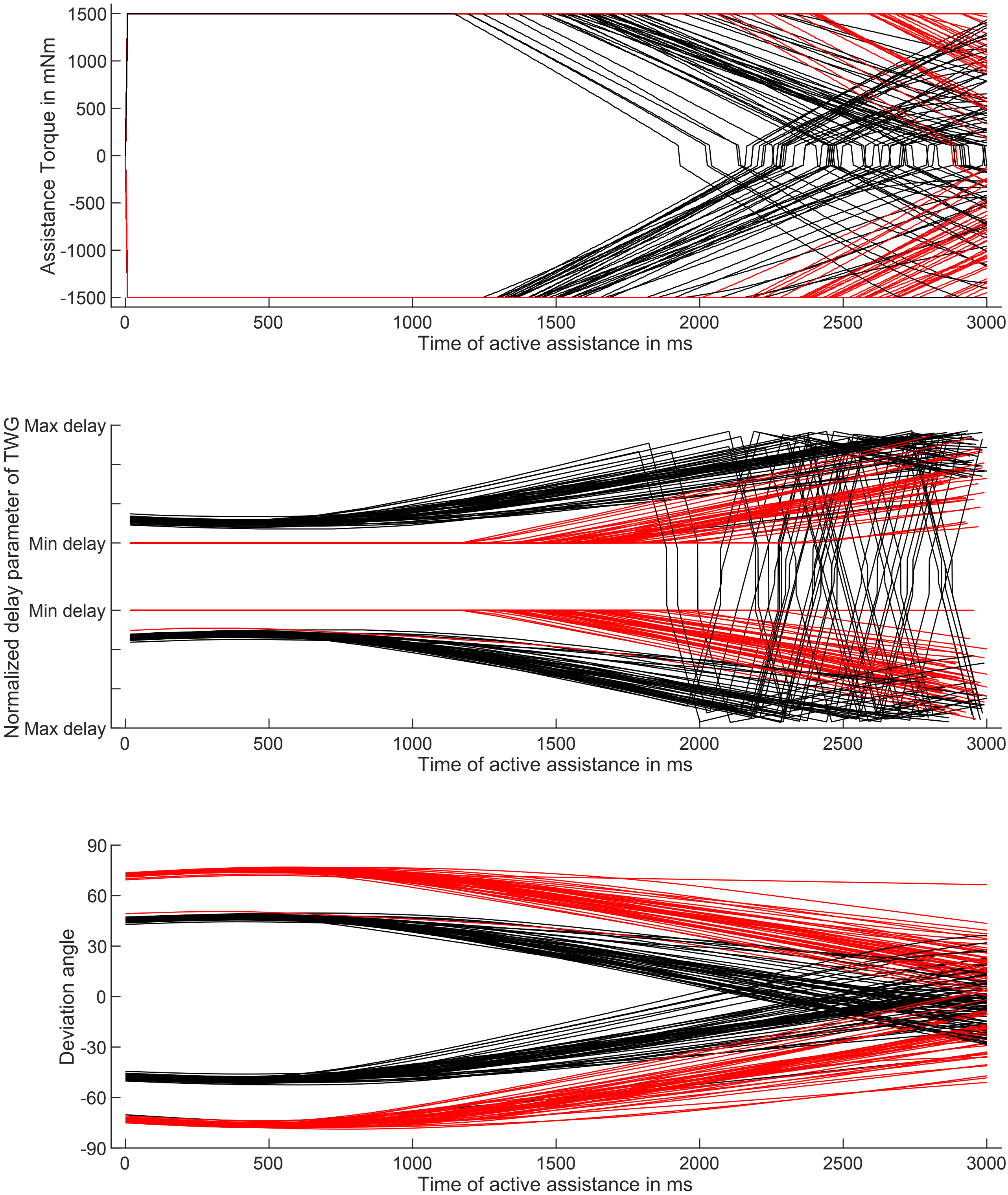


Figure 4.26: *Course of the assistance torque, illustrative course of* t_{delay} *and course of* α *for the four outmost portals. Drives for portals one & seven are shown in red, portals two & six in black. Positive and negative values for torque, upper and lower lines for delay parameters and positive and negative values for deviation angles result from clockwise and counter clockwise rotations. The area in the middle is skipped because of a minimal torque of 100 mNm and a minimal delay parameter of* $\geq$ *30 ms. All delay parameters are shown normalized for one minimal and maximal value. Actual courses of delay parameters are equal in quality but differ in quantitative value.*

Red lines represent the drives where portal one and seven were correct. The deviation angle was smaller for portals two and six at the assistance onset which is why the assistance torque declines from the saturation of $\pm 1500\ mNm$ earlier then for the drives with correct portals one and seven. Likewise these drives used the minimum delay parameter longer than/at all compared to the drives with correct portals two and six. The deviation angle crossed $0°$ on average 4.4 times (SD: 1.9) per drive (one drive including twelve scenarios relevant for analysis), which represents the times drivers had to switch the steering direction. The deviation angle didn't switch sign at all in 114 out of 179 scenarios (~ 64%).

4.2.3. Discussion of Study Two

The sample size was limited due to severe technical issues. TWG had to be repaired twice during the study before finally giving out completely on the right side during the first drive of subject 16. The first problem occurred with a set of solenoids on the right side. A thorough investigation revealed a broken solder point in the power line leading to this set. This was most likely caused by the rapid and extensive steering motions in this study. It was fixed by mechanically interlocking the two loose ends and fixating them with new shrink tubing. Two subjects later the same point ripped again. The problem was fixed by adding a new solder point. Finally, the entire right side of TWG stopped working, leading to the suspicion that the one central power line leading away from the solenoids was damaged. A quick search of the cable part close to the steering wheel rim revealed no broken part. This meant the damage was caused within the curly cable cover. More close-to-breaking points were discovered during the search for this fault. At this point the study was terminated early as the entire system was clearly not going to last through more participants. It became obvious that the initial requirement C-i (Tab. 3.1) could not be fulfilled due to the extensive steering force applied by the subjects. Shakeri, Brewster, et al. (2016) also needed some sort of electrical power supply, yet no technical setup or problems were reported. Quintal and Lima (2022) rate their vibration-only device as "robust and long-lasting" because it doesn't have any moving parts. This unfortunately proves to be a weak spot of TWG which has 48 solenoids with spatial movement. All systems from the literature have in common that their authors do not report any problems with the steadiness of their prototypes. Systems with up to 20 (Kim et al., 2012) or even 32 (Hwang & Ryu, 2010) vibration motors that sometimes were all active at the same time should have an impact of physical components of a steering wheel, especially when they are repeatedly activated in a user study. Other prototypes were used in real world driving environments (e.g., Ploch et al. (2016, 2017)) and must have been subject to bumps and vibrations from the road surface.

Participants chose eight different delay parameters. This supports the choice for a setting-per-subject approach instead of the one-size-fits-all like in the first study. Only four subjects landed in the area $\leq 50\ ms$ which corresponds to the values of $35\ ms$ and $50\ ms$ from the first study as well as to the ISO of $30\ ms$ used by Hwang and Ryu (2010). It is also interesting to see subjects choosing delay parameters up to $120\ ms$ as the minimum while Hwang and Ryu (2010), the first study to implement the wave pattern, reported difficulties for subjects to still identify the wave pattern when the stimuli rate was to low. It shows that perception of the wave pattern is highly dependent on the delay parameter. While Hwang and Ryu (2010) based their ISO on Hill and Bliss (1968), more recent research from Boldt et al. (2014) suggests much higher delay times might be necessary for sufficient perception. Other studies like Hwang and

Ryu (2010) or Quintal and Lima (2022) used fix time spans for their patterns as well but don't report individually adjusted times as a future implementation or improvement. On the contrary, Quintal and Lima (2022) praise their short activation span of $350\ ms$ as a possibility to execute more patterns in a certain time frame. Medeiros-Ward et al. (2010), who used skin shearing, used fixed times for participants as well, but the authors report that they "ensured that all participants could accurately perceive and interpret the tactile feedback before beginning the experiment" (Medeiros-Ward et al., 2010, p. 2046). It is possible that these other systems would benefit from the individual approach, as executed in this study, since the results from basic research mentioned above are ambiguous as well.

Still, any tactile pattern has the disadvantage of having to wait a finite time > $0\ s$ until a pattern is completed before all the information is transmitted. Torque on the other hand is time-continuous and requires a theoretically infinitely small time to apply a full information cue. This qualifies tactile systems more for continuous use cases, e.g., lane keeping, where no fixed ending exists. Further research could also incorporate the times a driver might need to properly process a perceived stimulation. Tactile stimulation time plus driver reaction time can disqualify such assistance systems even more from time critical scenarios.

The next question was wether the scenario design lead to torque and TWG activations at the intended times and with the intended values. This thesis focuses on the time torque is saturated at the safety limit. The torque was saturated for at least more than half of the activation time in both conditions torque-only and TWG&torque (Tab. 4.4). Torque was saturated longer for portals one & seven than for portals two & six because these drives started with a larger deviation angle. TWGs delay parameter spent less time at its minimum limit than torque spent at the saturation limit. This was intended and is a direct consequence from the angle limit of $60°$ for TWG and $30°$ for torque. This means the study design produced results as intended because this way TWG was able to offer distinguishable delay parameters while torque was still constant because of saturation.

The main question was whether a HSC drive supported by TWG would enable participants to choose a correct portal when torque was saturated. The statistical analysis in 4.2.2 gave a clear answer that this was not the case. It's not surprising that drivers performed significantly better in the torque-only drive compared to the TWG-only drive. Torque has the simple advantage that it actively steers the vehicle and doesn't only inform the driver. The more interesting question was whether the results from torque-only could be improved by adding TWG. TWG&torque slightly outperformed torque-only judging by absolute numbers, yet the advantage of only two missed portals less is by far not enough to produce statistical significance.

TWG and HSC had different parameters and activation values depending on the deviation angle. Future studies could use other values than $30°$ for torque and $60°$ for TWG as saturation angles, yet this choice will most likely be influenced by the real world application. These two values were chosen in this study in accordance with the geometric setup of the scenario, the vehicle speed and the torque limit. It is important though to always set a higher angle for TWG than for HSC since TWG doesn't have to incorporate requirements for active steering (s. chapter 4.2.1).

Table 4.5 shows that drivers covered significantly more lateral distance for portals one & seven compared to two & six in TWG-only than in the other two conditions. The same significant effect was found for the amount the yaw angle differed between portals one & seven and portals two & six. This is because torque had the same value for all four outmost portals for at least the time it was limited which was approximately $1.6\ s$. On the one hand, these results prove that TWG can provide distinguishable information that leads drivers to drive on different trajectories. On the other hand, TWG was not able overcome torques influence in the TWG&torque condition. It did not animate the driver to complement the systems torque in a way that would have also resulted in significantly different trajectories. There are two possible explanations: 1) Drivers let torque take over almost the entire steering task during the three second timeframe on purpose. Subjects were informed that the system would know the correct portal, so it's reasonable they let the system do as much as possible to get to the right portal in the end. If drivers then did not apply any noteworthy torque themselves, the trajectories for portals one & seven and two & six would not be significantly different. This would mean drivers willingly or unwillingly ignored TWG and its graded information input and only followed HSC. 2) Drivers were overwhelmed by both systems being active at the same time. The confusion paralyzed them to some extent which gave the HSC system the freedom to be the only active steering partner and dictate the trajectory.

The calculated ANOVAs produced medium effect sizes for the main effect and very large effect sizes for the post-hoc tests. While this supports the importance of TWGs influence on the trajectory, the smaller sample size of 15 datasets has to be taken into account, especially when interpreting Cohen's *d*.

TWG-only drives for portals two & six points barely reach the minimum delay parameter. This points to a better potential gradation of input signal on first sight. On the other hand, the maximum delay parameters are also never reached in any investigated TWG-only drive. Yet the results for correctly chosen portals don't show a significantly better performance for the TWG-only drives. This could mean that delay parameter values were not spread out enough to ensure subjects ability to properly distinguish between different wave speeds. It was intended to keep delay parameter values within the minimum-maximum range and avoid saturations like for torque. Yet the specific calibration in this study might have narrowed the parameter too much, leading to a tube of values that doesn't utilize the entire available range.

TWG-only allowed drivers to chose significantly different trajectories compared to drives with torque. The number of zero crossings also stands out for drives with TWG-only. TWG never switched the side of assistance in any scenario in the TWG-only drives. This points to less steering effort for drivers on first sight. Closer investigation reveals that the deviation angles for TWG-only converge towards $0°$ like in the other conditions, yet the assistance window ends before $0°$ is reached. Another indicator are the covered lateral distances and changes in yaw angle in TWG-only (Tab. 4.5). Drivers did not move the vehicle enough in the three seconds to trigger a change in assistance direction. Larger distances and yaw angle changes might have led to switches of the deviation angle sign but then maybe also to better performance when choosing the correct portal.

5. Conclusion

This thesis set out to evaluate whether tactile stimulation can replace information when torque as an information channel has to be limited. A driving simulator study revealed that drivers don't choose a correct trajectory more often when tactile stimuli supplement assistance torque at the steering wheel. Yet the results also reveal that drivers can distinguish between different tactile stimuli when no torque is present. This goes as far as drivers choosing significantly different trajectories when presented with different configurations of tactile stimulation.

Chapter 2 highlighted the possibilities of haptic information transmission when the human physiology was considered. The different tactile mechanoreceptors in the human skin presented in chapter 2.2 react to different stimulation, creating much more ways to reach a driver than the established vibration. Chapter 2.4 showed examples of how other research already made use of the drivers complex haptic channel.

Chapter 3 documented the construction process of TWG. Starting from simple prototypes made of paper and wood, TWG was evaluated early on in the development process. The first feedback revealed the potential of tactile pressure stimulation with test subjects already recommending specific changes, like an adjusted solenoid power depending on the urgency, to improve the otherwise widely accepted system. The following improvements focused on an important aspect: drivers wanted a proper steering wheel to work with TWG. This meant increased effort and cost - factors that are not present this much with visual or acoustic prototypes. It's important to note that systems from the literature also used prototypes with a physical mockup that represented a proper steering wheel. T. A. Kern et al. (2009) were the only exception but promptly reported this complaint by their subjects.

The final constructive improvements in chapter 3.3 focused on several technical issues that are also almost exclusive to haptic prototype devices. Visual and acoustic stimulations are separate from other sensory systems. Visuals usually don't create acoustic or haptic stimulations, acoustics usually don't create visuals. Haptics on the other hand still rely on physical contact and moving parts, even if the movements are small like with vibration. Acoustic stimulations were the major disturbing influence in this work. Chapter 3.3 showed that technical possibilities to deal with this exist, yet much more effort and budget is needed to reach sufficient effects. This handicaps haptic research in a research community, where resources like time and money are always scarce.

The studies in chapter 4 revealed one important factor that was not yet mentioned in the literature. Instead of just basing inter stimulus onset times (t_{delay}) only on average thresholds from basic research on human physiology, the per-subject approach yielded much better results. This approach focused on providing an equal perception instead of an equal technical setup for all subjects. Chapter 4 unfortunately also revealed a weakness of applied tactile research. Prototypes are prone to wear and tear if they are repeatedly used. This differs from research with visuals or acoustics. Yet the increased effort, cost and time that is needed for applied tactile research should not limit future works that can make use of the variety in human haptic perception.

The connection between torque and tactile stimulation can be investigated in different scenarios in the future. This work focused on a time critical scenario and situations where torque was limited as defined by the study design. This led to the intended saturation of torque, yet it also limited execution time for the tactile wave patterns. The scenario of continuous lane keeping assistance could be revisited with the final prototype and most importantly with the individual settings for the waves speeds. Future research could also focus on one aspect that was not further investigated: the shape, size and material of the pin tops. This topic was briefly addressed in chapter 3.1.4 but not followed up on. Using different pin tops to convey different urgencies of steering or using pin tops to enlarge the pressure area of a single pin remain open fields for investigation.

Based on the results of this thesis the recommendation is to not neglect the tactile channel as possible assistance for the steering task. It becomes clear that torque remains the most effective factor to influence a vehicles trajectory. Yet tactile stimulation offers the possibility to further distinguish use cases of assistance based on urgency. While torque could be reserved the most extreme scenarios, i.e. emergencies, tactile assistance can be implemented in normal driving situations. Tactile also offers an easier assignment of responsibility in case of an accident, because the driver remains the only one to actively influence the vehicles trajectory.

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Glossary

C

CAD - Computer Aided Design 18
COG - Center Of Gravity 28

H

HSC - Haptic Shared Control 1

P

POM - Polyoxymethylene 20

T

TWG - Tactile Wave Generator 2

Annex

Annex A Data from Study One

Table A.1: *Number of activations of each pattern in both speeds separate and combined for the* ***left*** *steering wheel side and hand for all 23 participants.*

#	Simple_-ipsi	Simple_-ipsi	Simple_-ipsi	Wave_-Single_ipsi	Wave_-Single_ipsi	Wave_-Single_ipsi	Wave_-Double	Wave_-Double	Wave_-Double
	50 ms	35 ms	Total	50 ms	35 ms	Total	50 ms	35 ms	Total
1	15	0	15	6	2	8	5	0	5
2	29	3	32	30	27	57	19	15	34
3	3	0	3	10	0	10	16	5	21
4	12	16	28	37	18	55	26	15	41
5	52	14	66	69	29	98	37	7	44
6	36	12	48	60	33	93	29	11	40
7	41	14	55	41	5	46	32	27	59
8	24	28	52	31	19	50	46	44	90
9	24	3	27	58	13	71	46	19	65
10	45	14	59	54	34	88	76	40	116
11	45	20	65	51	4	55	47	16	63
12	48	7	55	50	32	82	51	25	76
13	36	54	90	57	56	113	52	33	85
14	43	0	43	39	26	65	45	3	48
15	3	0	3	26	8	34	9	6	15
16	47	7	54	36	27	63	34	13	47
17	48	22	70	47	38	85	57	26	83
18	58	29	87	58	64	122	71	33	104
19	73	42	115	59	60	119	80	47	127
20	65	28	93	49	54	103	60	57	117
21	58	103	161	60	86	146	41	107	148
22	12	6	18	24	5	29	14	8	22
23	35	41	76	57	126	183	27	18	45

Table A.2: *Number of activations of each pattern in both speeds separate and combined for the **right** steering wheel side and hand for all 23 participants.*

#	Simple_-ipsi	Simple_-ipsi	Simple_-ipsi	Wave_-Single_ipsi	Wave_-Single_ipsi	Wave_-Single_ipsi	Wave_-Double	Wave_-Double	Wave_-Double
	Slow	Fast	Total	Slow	Fast	Total	Slow	Fast	Total
1	23	16	39	29	0	29	11	1	12
2	26	4	30	30	19	49	30	13	43
3	19	8	27	7	3	10	5	0	5
4	22	13	35	19	11	30	31	20	51
5	0	0	0	4	4	8	5	3	8
6	19	9	28	13	1	14	22	16	38
7	16	2	18	19	2	21	21	5	26
8	21	10	31	12	4	16	10	8	18
9	13	0	13	7	5	12	2	0	2
10	2	0	2	7	0	7	4	0	4
11	13	5	18	5	0	5	18	7	25
12	16	22	38	9	0	9	19	14	33
13	10	12	22	5	3	8	11	0	11
14	15	4	19	2	0	2	21	0	21
15	7	0	7	3	1	4	5	0	5
16	13	14	27	22	19	41	18	16	34
17	6	0	6	10	6	16	4	2	6
18	3	0	3	5	1	6	1	5	6
19	7	3	10	3	6	9	23	14	37
20	14	2	16	20	3	23	10	6	16
21	11	2	13	12	7	19	18	8	26
22	7	13	20	7	0	7	26	5	31
23	5	6	11	10	12	22	6	5	11