On the Influence of Action Preparation on Steering Performance in a Lane Change Task

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Zusammenfassung

Kognitiv psychologische experimentelle Untersuchungen der Handlungsvorbereitung und der Bewegungsausführung finden gemeinhin unter hoch kontrollierten Bedingungen im Labor statt. Es ist allgemein anerkannt, dass adäquate zeitliche und inhaltliche Handlungsvorbereitung die Reaktion des Individuums unterstützen, was sich z.B. in verkürzten Reaktionszeiten auf imperative Stimuli zeigt. Verkehrspsychologische Forschung wird dagegen häufig unter realitätsnahen Bedingungen, z. B. im Feld bzw. in modernen Fahrsimulatoren durchgeführt. In diesem Forschungsbereich ist kaum untersucht, inwieweit Mechanismen der Handlungsvorbereitung die Reaktionen eines Fahrers unterstützen. Trotz der unterschiedlichen Ansätze erscheint das Konzept der Handlungsvorbereitung als durchaus anwendbar auf fahrerische Lenkbewegungen, da das Fahren an sich die stete Antizipation direkt bevorstehender bzw. zukünftiger Verkehrssituationen erfordert. Ausgehend von dieser Annahme verfolgt diese Dissertation drei Ziele. Erstens galt es, grundlagenorientierte experimentelle Forschungsparadigmen der Handlungsvorbereitung, insbesondere zeitliche und ereignisbezogene Vorbereitung, in eine anwendungsorientierte Fahraufgabe zu integrieren. Zweitens sollten grundlagenorientierte kognitionspsychologische Vorhersagen in dieser angewandten Umgebung getestet werden, um entsprechende Befunde zu replizieren bzw. zu erweitern. A priori besteht keine Sicherheit darüber, ob zeitliche und ereignisbezogene Vorbereitung tatsächlich zu mit den Grundlagen vergleichbaren Ergebnissen in einer Fahraufgabe führen, da sich eine kontinuierliche Fahraufgabe mit komplexen beidhändigen Lenkbewegungen deutlich von einer Einzelfingerreaktion in einer typischen Laboraufgabe unterscheidet. Drittens sollte eines der grundlagenorientierten Paradigmen modifiziert und anhand einer angewandten Fragestellung eingesetzt werden, um die Nützlichkeit grundlagenorientierter Forschungsparadigmen zur Untersuchung konkreter Probleme beispielhaft zu demonstrieren.

Zu diesem Zweck wurde eine Spurwechselaufgabe in einem Labor für virtuelle Realität entwickelt. Mit Hilfe dieser experimentellen Fahraufgabe wurden zeitliche und ereignisbezogene Handlungsvorbereitungsprozesse in einer ersten Serie von fünf Experimenten untersucht. Zeitliche Vorbereitung wurde im Rahmen eines variablen Vorperiodenparadigmas implementiert, ereignisbezogene Vorbereitung in Übereinstimmung mit dem Movement Precuing bzw. dem Response Priming Paradigma. Neben der Reaktionszeit auf imperative Spurwechselsignale wurden kinematische Eigenschaften der

Spurwechsellenkbewegung analysiert. Dazu wurde die gesamte Spurwechsellenkbewegung in drei Einzelbewegungen unterteilt, von denen letztlich die ersten beiden anhand ihrer Geschwindigkeitsprofile ausgewertet wurden. Grundsätzlich wurde vorhergesagt, dass zeitliche und ereignisbezogene Handlungsvorbereitung Reaktionszeitverkürzungen zur Folge haben und somit zu der Grundlagenliteratur ähnlichen Reaktionszeitmustern führen sollten. Darüber hinaus und übereinstimmend mit der „movement integration"-Hypothese (Adam et al., 2000) bzw. Ergebnissen von van Donkelaar und Franks (1991a) wurden kinematische Effekte um das erste Lenkwinkelmaximum der Spurwechsellenkbewegung erwartet. Schließlich dienten ein sechstes und ein siebtes Experiment der Untersuchung des angewandten Problems, ob ein 3-dimensionales kontaktanaloges Head-Up Display (HUD) die Handlungsvorbereitung effektiver als ein 2- oder 2½-dimensionales HUD unterstützt.

Die Ergebnisse der Experimentalserie waren mannigfaltig. Im Hinblick auf die ersten fünf Experimente wurden grundsätzlich die aus den Grundlagen bekannten Reaktionszeitergebnisse repliziert. Spezifischer betrachtet zeigten sich deutlichere Effekte ereignisbezogener als zeitlicher Handlungsvorbereitung. Das Movement Precuing führte zum bekannten „precuing effect", d.h. mit zunehmender Vorinformation über einen anstehenden Spurwechsel verkürzten sich die Reaktionszeiten. Das Response Priming zog den bekannten „validity effect" nach sich, d.h. die Reaktionszeiten fielen für neutral vorbereitete Spurwechsel länger als für valide und kürzer als für invalide vorbereitete Spurwechsel aus. Zeitliche Vorbereitung führte zwar immer zu kürzeren Reaktionszeiten als gar keine Vorbereitung, aber die Unterschiede zwischen verschiedenen Vorperioden fielen im Gegensatz zu Grundlagenerkenntnissen nur gering aus. In zwei Experimenten ergaben sich zudem instabile Interaktionen zwischen zeitlicher und ereignisbezogener Handlungsvorbereitung. Diese Ergebnisse deuten daraufhin, dass sich beide Arten der Vorbereitung gegenseitig beeinflussen können. Im Gegensatz zu zeitlicher Handlungsvorbereitung hatte ereignisbezogene Handlungsvorbereitung einen systematischen Einfluss auf kinematische Eigenschaften der Lenkbewegung. Movement Precuing und Response Priming neigten zuverlässig dazu, die Länge der beiden kinematischen Phasen um das erste Lenkwinkelmaximum zu verkürzen. Diese Verkürzung wurde als erhöhte Effizienz der Lenkbewegung interpretiert, da sich keine zusätzlichen Kosten im Sinne einer schlechteren Steuerqualität ergaben. Die Ergebnisse der Experimente sechs und sieben fielen nicht hypothesenkonform aus. Anstelle des 3-dimensionalen HUDs unterstütze das 2-

dimensionale HUD die Handlungsvorbereitung am effektivsten, was unter Umständen den überlernten einfachen zweidimensionalen Pfeilsymbolen zugeschrieben werden kann.

Zusammenfassend belegt diese Dissertation die Relevanz der Handlungsvorbereitungskonzepte für Fahrmanöver. Die Reaktionszeitergebnisse weisen auf vergleichbare Mechanismen der Informationsverarbeitung bei einfachen Reaktionszeitaufgaben und komplexen, kontinuierlichen bimanuellen Steueraufgaben hin. Darüber hinausgehend scheint ereignisbezogene Handlungsvorbereitung auch der Optimierung der Bewegungsausführung zu dienen. Basierend auf diesen Hinweisen könnten sich weiterführende Studien auf die Interaktion zwischen zeitlicher und ereignisbezogener Handlungsvorbereitung, auf zusätzliche Fahrmanöver in realistischeren Szenarios oder auf den Nutzen dieser Spurwechselaufgabe als diagnostisches Instrument konzentrieren.

Abstract

Cognitive psychological experimental work on response preparation is generally conducted under highly controlled laboratory conditions. Adequate temporal as well as event-specific preparation typically support the individual's response preparation, for example in terms of reduced reaction times (RT) on imperative stimuli. By contrast, psychological research on driving tends to be conducted under realistic conditions, for example in the field or in sophisticated driving simulators. This research has largely overlooked the extent to which mechanisms of action preparation support the driver's reactions. Despite these two different approaches, the concept of action preparation should be highly applicable to vehicle steering, since driving requires the driver continuously to anticipate immediate and future traffic situations. Starting from this assumption, this dissertation's first aim is to transfer basic experimental paradigms on action preparation – that is, temporal and event-specific preparation – into a driving task. Second, the predictions derived from cognitive psychological groundwork will be tested in this applied setting in order to replicate and enhance the corresponding findings. A priori it was not clear whether temporal and event-specific preparation would lead to comparable results in a driving task, since a continuous driving task with complex bimanual steering movements is quite different from discrete single finger reactions in a typical laboratory task. Third, one of the basic paradigms on action preparation will be modified and transferred to an applied question in order to exemplify its usefulness for concrete problems in driving research.

For these purposes, a lane change task was developed in a virtual reality environment. With the help of this experimental driving task, processes of temporal preparation as well as of event-specific preparation were examined in a first series of five experiments. Temporal preparation was implemented according to a variable foreperiod paradigm, while event-specific preparation was realized according to the movement precuing and the response priming paradigm. Aside from measuring the reaction time (RT) on the imperative lane change signals, kinematic properties of the lane change steering wheel movement were evaluated. To this end, the entire lane change movement was divided into three submovements, the first two of which were eventually analyzed in terms of their velocity profiles. It was generally predicted that temporal and event-specific response preparation would reduce RTs and lead to result patterns comparable with evidence in the respective cognitive psychological literature. In keeping with the "movement integration"-hypothesis

(Adam et al., 2000) and in accordance with the findings of van Donkelaar and Franks (1991a), kinematic effects were expected around the first peak steering wheel angle of the lane change steering wheel movement. Eventually, the sixth and seventh experiment served to examine the applied question whether a 3-dimensional conformal head-up-display (HUD) supports response preparation more effectively than a 2- or 2½-dimensional HUD.

This experimental series produced a variety of results. With regard to the first five experiments, RT patterns known from basic research were replicated. More specifically, the effects of event-specific preparation were more pronounced than those of temporal preparation. Movement precuing led to the "precuing effect" – i.e., the more advance information on a lane change was available, the shorter the RT. Response priming led to the "validity effect": RT on neutrally prepared lane changes was longer than RT on validly prepared lane changes and shorter than RT on invalidly prepared lane changes. Temporal preparation always led to shorter RT than no preparation at all. But, contrary to the literature, the differences between different foreperiods were only shallow. Although unstable, interactions between temporal and event-specific preparatory processes occurred in two experiments. These results support the idea that both processes might mutually influence each other. Temporal preparation did not influence the kinematic properties of the steering wheel movement systematically, although event-specific preparation did. Movement precuing and response priming tended reliably to shorten the duration of the two kinematic phases centered around the first peak steering wheel angle. Since this shortening was not accompanied by increased costs in terms of lower steering quality, this modification was interpreted as increased movement efficiency. The results of Experiment 6 and 7 were not compliant with the hypotheses. Instead of conformal 3-dimensional HUDs, 2-dimensional HUDs tended to support response preparation most effectively. This effect is possibly due to the overlearned nature of simple 2-dimensional arrows. In conclusion, the thesis offers evidence for the relevance of concepts of response preparation for driving maneuvers. The RT results point to comparable mechanisms of information processing in simple RT tasks and more complex continuous bimanual steering tasks. Event-specific response preparation also seems to optimize response execution. Based on this evidence, future directions of this research might consist in further examining interactions between temporal and event-specific preparation, analyzing additional driving maneuvers in more realistic scenarios or making use of the lane change task as potential diagnostic tool.

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1 Introduction

Nowadays a driver of a modern vehicle is supported by a multitude of advanced driver assistance systems (ADAS), such as lane departure warning, lane change assistance, adaptive cruise control, forward/rear-end collision warning, hill descent control or driver drowsiness detection. ADAS are systems that partly support or even take over the driver’s tasks. Their aim is to reduce or eliminate driver errors and thus to generate a positive effect on traffic safety. For this purpose, these systems try to facilitate the drivers’ task performance by providing real-time advice, instructions and warnings (Brookhuis, de Waard, & Janssen, 2001). Interestingly these systems also try to enhance or complete the driver's cognitive picture of certain traffic situations by delivering information that would normally not be directly accessible. Examples for such ADAS are blind spot detection, traffic sign recognition, night vision, intersection collision avoidance and navigational information systems. However, the effectiveness of ADAS depends largely on the driver's conditions and limitations (Lindgren & Chen, 2007) and might even change the driver's task from a manual to a supervisory role (Carsten & Nilsson, 2001). Consequently, ADAS present not only a technical engineering challenge but also a psychological one and thus the car driver’s working environment has inspired a large amount of cognitive psychological research in the last decades. In view of the continuously emerging technical progress the question is this: How much does ADAS information increase or decrease the driver’s cognitive information processing performance? The additional “cockpit” complexity might increase the risk of driver failure, the driver might be taken out of the loop or poor system design might affect the driver’s performance adversely (Brookhuis et al., 2001). Thus, from a cognitive psychological perspective, many issues concerning the design and implementation of ADAS still have to be resolved. One important aim of most ADAS presenting information to the driver is to prepare him or her for a certain event or a certain action at a certain point of time. It is obvious that well established basic cognitive psychological concepts such as the concept of action preparation (Requin, Brener, & Ring, 1991) can be judged as relevant for this field of research. However, not only new in-vehicle technologies support the driver’s action preparation; other sources of information, such as conventional dashboard instruments and road signs, prepare drivers for upcoming actions as well (Crundall & Underwood, 2001;

Koyuncu & Amado, 2008). Preparation for action appears to be a central aspect of information processing in driving.

The purpose of this work is to transfer the concept of action preparation to an applied driving task and to work out to what extent findings from basic research can be replicated in this task. Thus theoretical concepts of basic research might be generalized to a more applied context. How far does this enterprise make sense? In general, driving can be regarded as a complex operation (Cummings, Kilgore, Wang, Tijerina, & Kochar, 2007; Salvucci, Liu, & Boer, 2001) that is difficult to subdivide into its constituting functions. As a consequence, one could argue that research about driving makes only sense in the field or at least in complex, realistic driving simulators. But the more realistic the experimental approach gets, the more difficult it is to extract, isolate and interpret relevant mental processes. This fact is due to the general difficulty of cognitive research in that cognitive processes cannot be observed directly. Changes in cognitive processing are generally inferred indirectly from changes in oxygen supply in certain brain areas, from changes in the electrophysiological pattern of the electroencephalogram (EEG) or from changes in movement and reaction times (MT and RT). For the purposes of this work, the RT and MT approach has been chosen in order to measure covert cognitive processing as well as its consequences for overt behaviour. It implies that even small changes in RT or MT caused by the variation of experimental factors indicate changes in mental processing (Miller, 1982; Sternberg, 1969). As RT often undergoes a large variability (e.g. due to biological noise) experimental conditions have to be repeated many times in order to guarantee sufficient statistical power for according analyses. This requirement is a critical one for each naturalistic approach, since complex experimental situations that aim to represent behaviour in normal life cannot be repeated often enough in the field or in a realistic driving scenario. Consequently there is a trade-off between ecological validity and experimental control of any experiment (Loomis, Blascovich, & Beall, 1999). One may assume that a transition from rather reductionist experimental control to rather complex ecological validity is a matter of generalization. However, it is not justified to generalize experimental results directly to the "world outside" (Heuer, 1988b) unless the experiment can be considered to be a simulation of the reference situation in question. It seems to be more appropriate to use highly controlled experimental situations in order to confirm theoretical statements about the system (or subsystem) in question, which is to say to corroborate a certain theory. Although such theories in the biological sciences cannot be regarded as deterministic laws, they still serve to limit the range of possible solutions in applied problems (Heuer, 1987a, 1988b). According to Heuer it is up to the practitioner to combine theoretical knowledge from basic research with experience and intuition in order to solve applied problems. Nevertheless, the reductionist approach of basic research renders this transfer of theoretical knowledge to applied problems difficult at times, since the ecological validity and relevance of a basic experiment for driving performance is not always apparent. As mentioned before, this is partly due to the fact that basic research often focuses on certain subsystems of human performance. In cognitive psychology these subsystems might be perception, memory, decision making or psychomotor processes. By contrast, applied research focuses on human performance as a whole product that does not necessarily need to be broken down to its constituent parts. Especially in the field of driving, this gap between basic and applied research seems to be quite large, impeding the transfer from basic research evidence to the application. For this reason, well-controlled experiments combining basic and applied concepts can contribute to a gradual knowledge transfer between both fields of research that eventually can lead to practical benefits for the users of any advanced technology.

The principal idea of this thesis is to contribute to filling this gap by demonstrating the validity of basic research evidence about action preparation in an applied context and thus to asses to what extent theoretical concepts can be generalized to more complex environments. To this end, a driving simulation was developed which allows transferring basic paradigms to a more applied but nevertheless still highly controllable experimental driving environment. The main advantages of this approach are three: First, it provides the necessary experimental control and statistical power allowing inferences about cognitive processes. Second, it demonstrates that certain cognitive paradigms can be deployed in an applied setting. This might help the practitioner to base his or her problem solution on a robust theoretical fundament. Third, it shows that these paradigms can be adapted and modified in order to investigate specific applied problems. Thus, the practitioner might receive helpful instruments and approaches to the solution of applied problems.

A lane change task was developed and deployed as a concrete driving task for the validation and enhancement of the concepts of action preparation. From an experimental perspective, lane change tasks can be regarded as well established applied driving tasks (Mattes, 2003) that are easy to learn and that allow experimental control as well as causal interpretations of experimental effects. From a practical view, lane changes as a daily routine maneuver provide high ecological validity (Salvucci, Liu et al., 2001). In addition, lane changes are highly relevant for traffic safety since they often become the origin of accidents (Sivak, Schoettle, Reed, & Flannagan, 2006). In order to minimise this risk, longitudinal and lateral vehicle control can be supported by various ADAS, such as lane change assistance, lane departure warning and lane keeping support. In sum, the lane change maneuver seems to represent an adequate example of an applied driving task for the examination of cognitive basic research concepts.

The final ingredient for the experimental series described in this work is the information display selected for communicating any relevant preparatory information to the driver: the head-up display (HUD). HUDs constitute transparent displays that present information to the driver directly into his forward field of view, appearing to float directly over the road in a distance of about 2-3 meters in front of the vehicle (Tufano, 1997; Ward & Parkes, 1994). For the current experiments, HUDs were chosen as information display technology since they probably interfere less with action preparation than conventional head-down displays (HDD) may (see section 1.3.5).

The following sections serve introductory purposes, detailing the theoretical backgrounds of the different concepts referred to in this work.

1.1 Motor Control and Kinematic Aspects of Response Execution

The concept of action preparation implies that actions and reactions performed by the motor system can be prepared. To analyze these effects of preparation, one must first develop an understanding about how movements can be described from a psychological perspective. This section illustrates psychomotor concepts of motor control and movement execution as well as experimental approaches that serve to measure changes in movement execution. Since it is not feasible to review the entire historical development of psychological perspectives on motor control adequately, the following sections are necessarily limited to the basics required for this thesis. Thus, the sections mainly focus on the development and application of the motor programming metaphor in psychological research. However, the section also includes a short view on a more recent concept applied in research about action control: the ideomotor principle. In the following section, the characteristics of a bimanual steering movement will be described. It will be argued that, from a motor programming perspective, bimanual steering movements can be treated like unimanual movements.

1.1.1 Motor Programs, Kinematic Analysis and Ideomotor Control

According to the computer metaphor definition of Keele (1968), a motor program consists of a plan for a certain movement. This plan contains a certain "set of muscle commands that are structured before a movement sequence begins" (Keele, 1968, p. 387). The execution of this set of muscle commands leads to a movement that can be run without feedback from the periphery. If a motor program is fired off this way, it is executed in an "open-loop" or "ballistic" mode. Such an open-loop system does not dispose of compensatory capabilities in case of unwanted results, since the motor program executes a centrally stored plan for the movement and it is only the plan that controls the movement during execution (Adams, 1971). This open-loop concept was supported by experimental evidence showing that skilled movements can be performed without proprioceptive feedback and that expectancy about the features of an upcoming movement can lead to changes in its execution (Requin et al., 1991). In this sense, motor programming requires the preprocessing of information before the response execution. However, the open-loop perspective on motor control does not account for error detection and movement corrections during movement execution (Adams, 1976). For such corrections to occur, the processing of feedback from the periphery, for example as proprioceptive feedback or as exteroceptive feedback, is required and constitutes a central aspect of movement execution (Greenwald, 1970). If feedback is processed during movement execution, it is assumed to be integrated into the ongoing action, particularly in order to correct for errors. Theories of psychomotor behaviour focusing on this aspect are so-called "closed-loop" theories.

With this background, Adams (1971) assumed the "memory trace" – an initial motor program – to specify movement direction and the earliest portions of the movement. After the memory trace has initiated the movement, the "perceptual trace" takes over steering the limbs along the trackway into the intended target position. The perceptual trace is formed from the past feedback experiences with this movement, so that it knows the movement's sensory consequences. It permanently compares this stored experience with the incoming feedback from muscles and nerves and leads to adjustments until the limb arrives in the correct position. Schmidt (1975) emphasizes the strengths of Adams's theory with regard to simplicity, empirical evidence, learning of new motor tasks and its clear relation to linear positioning. However, it remains unclear how far linear positioning can be considered as representative for skilled motor behaviour and to what extent this theory can be applied to rapid movements. Another subject of criticism was the required experience of a certain movement to develop the corresponding perceptual trace, since individuals are able to execute movements accurately without having executed the respective movement beforehand. An additional problem of Adams's theory consists in the so-called storage problem. According to his theory, each single movement requires a corresponding motor program and a sensory reference – that is, memory and perceptual trace – in each individual's memory. This requirement is assumed to overtax the central nervous system (CNS).

Schmidt (1975) tried to overcome the limitations of Adams's theory, especially the storage problem, with the introduction of the "generalized motor program" (GMP). In contrast to the mere motor program (Keele, 1968), the GMP describes a class of movements with the same general structure. The production of a specific movement requires the determination of the GMP's general parameters before movement execution. "Thus, the performer's problem in choosing a movement is the determination of the response specifications that will modify the existing stored motor programs" (Schmidt, 1975, p. 232). Schmidt (1976) detailed the understanding of feedback processing during movement execution by making a distinction between response execution and response selection. Since the neuromuscular system operates on muscle spindle level with feedback loop durations such short as 30-50 ms, the path deviations of ongoing short (< 200 ms) movements can be corrected by the motor program during execution. However, the selection of a new motor program due to any environmental feedback processing does not seem to be possible for such short movements (Schmidt, 1975, 1976; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Although GMPs are generally used to explain the programming of rapid motor acts, Schmidt et al. (1979) and Schmidt (1976) assumed that movements can also be programmed when MT is long (i.e. MT > 200 ms and up to some seconds).

The concept of the GMP implies that movements belonging to the same class dispose of certain invariant properties, although they might be very different from each other (Schmidt et al., 1979). The theory of GMP has inspired a large deal of research trying to discover these invariant features of motor responses, especially by analyzing the kinematic properties of movements. This analysis is able to detect invariant properties of GMPs, especially in the timing of certain movement segments. If certain movements are executed either slowly or fast, then subjects tend to “expand” or “compress” the movement segments belonging to the entire movement (Shapiro, Zernicke, Gregor, & Diestel, 1981) according to the temporal requirements. In order to analyze the relative temporal proportions of movement segments, kinematic movement properties are investigated. In this context the movement trajectory – the spatial position of the involved limbs at different points in time (see Figure 1) – can be regarded as a common characteristic. The rate of positional change in time is defined as the movement’s velocity and can be calculated as the trajectory's first derivation. The second derivation of the trajectory represents the velocity’s rate of change in time, i.e., the movement’s acceleration. Movement segments can then be defined based on maxima and minima of the respective functions. Segments such as the time to peak velocity, the time after peak velocity, time to peak acceleration or time after peak acceleration can be defined and measured. In general, the analysis of changes of movement trajectory, movement velocity and movement acceleration profiles constitutes a common approach to the kinematic analysis of movements (Schmidt & Lee, 1998).

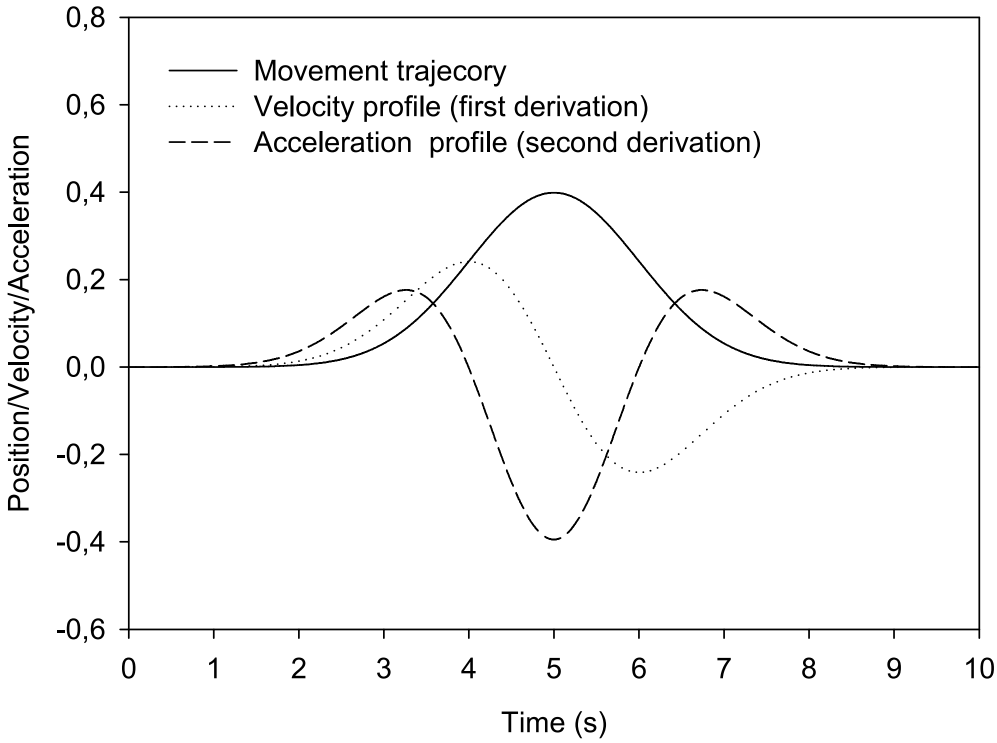

Figure 1: Example of an artificial movement trajectory with corresponding velocity and acceleration profiles.

Support for the existence of invariant properties of GMPs was derived from many studies investigating diverse tasks. Shapiro et al. (1981) mentioned that consistent proportional timing was found in typing, serial key-pressing, lever rotations and handwriting. These authors found evidence for invariant GMP properties in such complex actions as walking and running. However, not all attempts to isolate invariant GMP properties were successful. Zelaznik, Schmidt and Gielen (1986) tested the assumption of GMPs that aimed hand movements should exhibit time rescalability – in other words, that the temporal pattern of the movement phases was invariant across different MTs. Their results contradicted this assumption, since the time to peak acceleration was invariant across MT. Thus, the time rescalability is not necessarily a prerequisite of GMPs. It can be concluded that considerable evidence is available showing that the GMP concept is able to describe a large variety of movements. However, other studies put in question whether movement planning and control can be entirely explained by parameter adjustment of a general base program. For example, Marteniuk et al. (1987) found significant changes in the acceleration and deceleration phases of velocity profiles of comparable movements, which varied with regard to context variables such as movement target or intended effect. These authors concluded that movement execution is mainly influenced by specific task constraints based on experience, but not based on abstract representations of the movement.

Velocity profiles of movements do not only help search for invariants in GMPs. They also deliver information about advance movement planning processes as well as about visual feedback processing during movement execution. The trajectory formation can be regarded as the result of the planning and control of the kinematics of the movement (Marteniuk et al., 1987). According to the "two-component model of limb-control" (Beggs & Howarth, 1970; Carlton, 1981; Elliott, Helsen, & Chua, 2001), the initial (ballistic or open-loop) phase of a goal-directed aiming movement can be programmed in advance, whereas the second phase is under visual control. Since the minimum processing time for visual feedback is estimated to 100-135 ms, only the shortest movements seem to be executed in an exclusively open-loop mode (Elliott, Binsted, & Heath, 1999). Typically, the first (open-loop) phase of the movement lasts until the movement has reached its peak velocity. It mainly serves to move the limb into the vicinity of the target. During the second (closed-loop) phase of the movement, the "homing-in" phase, adjustments to the trajectory based on visual feedback can be made (Cullen et al., 2001). From the temporal pattern, i.e., from the duration of these two phases, inferences about the effects of movement planning and feedback processing can be made. According to Elliott et al. (1999), subjects try to make maximal use of visual feedback when practicing movements. Hence, they reach higher peak velocities earlier in the movement and have therefore more real processing time for visual feedback in the second closed-loop movement phase.

Kinematic movement analyses were also deployed to analyze movement sequences. Carter and Shapiro (1984) delivered evidence for the existence of invariant properties of GMPs in rapid sequential limb movements. They analyzed the kinematic characteristics of a movement sequence that was performed at moderate and at quickest possible speed. They found that MT decreased and average peak velocity increased when the movement sequence was performed as quickly as possible. However, the temporal proportions between the single movements of the sequence as well as the proportional time fraction required to reach peak velocity remained invariant between both conditions.

Movements in a movement sequence seem to be functionally dependent on one another. It was found that increasing difficulty of a second movement in a series of two movements led to longer MTs, longer times to peak velocity and longer decelerative phases of the first movement (Rand, Alberts, Stelmach, & Bloedel, 1997). According to Rosenbaum (1991) such context effects can be understood as program control, representing a program that controls the entire sequence instead of two programs controlling each segment. Only a substantial increase in movement difficulty of the first movement leads to a separate organisation of both movements, so that any interdependence between both of them is eliminated (Rand & Stelmach, 2000). GMP models also support the notion that movement sequences, especially reversal movements, are internally represented by a single motor program that defines the temporal movement structure (Schmidt, Sherwood, & Walter, 1988). Another finding that illustrates a functional interdependence between sequential movements was found by Glencross (1980), who described the “one-target advantage” (OTA). In this study instructions were either to move as fast as possible to a first target and either stop the movement or contact the first target and then move on to the second target. MT to the first target was consistently shorter in the first condition than in the second. Thus, the effect of a second movement seemed to consist in slowing down the first. One explanation for the OTA was brought forward by Chamberlin and Magill (1989). These authors claimed that the OTA is due to online-programming of the second movement during execution of the first one. A slightly different explanation was given by Ricker et al. (1999), who also attributed the OTA to online programming during the first movement, but according to them the rough motor program for both movements can be formulated prior to movement onset. Thus, the OTA seems to be composed of online programming as well as of additional visual feedback processing required to adapt the initial entire movement plan.

Yet another explanation for the OTA was formulated by Adam et al. (2000). These authors found that the OTA is eliminated in reversal movements. This finding led to the "movement integration"-hypothesis. It posits that the implementation of the second movement does not have to wait for the termination of the first one, but is partially overlapped with the execution of the first one. The OTA therefore is a result of interference between the neuromuscular organization of the second movement with the muscular execution of the first one. In the case of a reversal second movement, the antagonistic activity of the first movement during the homing-in phase can be exploited as agonistic activity for the initiation of the second one. According to Adam et al. (2000), reversal movements are optimally integrated in a close relationship. In addition, these authors claim that reversal movements can be programmed prior to movement onset. Cullen et al. (2001) relativize this last assumption, as they do not consider the programming of longer reciprocal movement sequences to be possible. Although OTA studies focused on fast and ballistic rapid aiming movements (e.g. Adam et al., 2000; Chamberlin & Magill, 1989), the movement integration-hypothesis could also be confirmed for more difficult single arm movements with longer MTs, suggesting operative visual and kinaesthetic feedback loops during movement execution (Helsen, Adam, Elliott, & Buekers, 2001).

Apart from the motor programming perspective, another more recent view on the control of movements needs consideration. This view is called the "ideomotor" approach to action control, otherwise known as the ideomotor principle (Greenwald, 1970). Although the formulation of this concept goes back to the beginning of the 19^{th} century (Stock & Stock, 2004), it only recently received heightened interest in cognitive psychology (Hommel, 1996; Prinz, 1987, 1990). The basic idea of the ideomotor principle is that actions are cognitively represented in terms of their anticipated action effects, or sensory consequences (Koch, Keller, & Prinz, 2004). The idea of an action effect can lead to the generation of an action that produces this effect. In other words, an actor can voluntarily select and start an action by activating the intended movement's effects. Hommel (1996) as well as Hommel et al. (2001)

translated this idea into the "motor programming" language by finding analogies in the theories of Adams (1971) and Schmidt (1975). The first two authors assume a kind of action concept (a cognitive code) that refers to the effects an action might produce and a motor program that is linked to this cognitive code. This concept resembles the idea of a perceptual trace and a memory trace in Adams's theory (1971) or the parameters and invariants in Schmidt's approach (1975). "Whenever and by whatever means an action effect code, or an action concept comprising several effect codes, is activated (for example by imagination or external stimulation) the motor program is activated, too, at least to a certain degree" (Hommel, 1996, p. 176). The ideomotor principle first requires that associations between actions and their corresponding action effects are built. Second, it requires that they can be reversed, which is to say associations are assumed to be bidirectional, so that the anticipatory representation of the intended action effect can trigger the required action. Several authors (see e.g. Elsner & Hommel, 2001; Hoffmann, Stoecker, & Kunde, 2004; Koch et al., 2004) found evidence for these assumptions, so that the integration of action effects into the planning and control of action is nowadays practically and theoretically well-established (Hommel, Müsseler et al., 2001; Prinz, 1997).

However, it is unclear to what extent the findings described in this section can be generalized to a driving context. This is due to the fact that basic research about GMPs as well as about ideomotor action is mostly concerned with simple and short movements such as single arm or finger movements. In contrast, steering wheel movements in driving are typically performed with both arms clinging to the wheel. Such movements are rather long in duration as compared with unimanual aiming movements. In the next section, the characteristics of steering wheel movements will be described and linked to motor program theory.

1.1.2 Characterization of Bimanual Steering Wheel Movements

The principal movement on which this study focuses is a lane change steering wheel movement in a vehicle. A both-handed steering wheel movement consists of point-symmetrical, reversal and rotating bimanual movements that are highly coupled in their spatial and temporal parameters. Obviously, this tight linkage between both hands is due to the wheel connecting both effector sides. Moreover, the actions of both arms serve the same effect – as opposed to pursuing independent effects, such as performing a unidirectional movement with one hand and a reversal movement with the other hand (a typical characteristic of asymmetric movements) (see e.g. Swinnen & Walter, 1991; Swinnen, Young, Walter, & Serrien, 1991). For these reasons and as will be argued in the next paragraphs, it seems to be reasonable to assume that such steering wheel movements may be controlled by the CNS as a single unit.

As was proposed by GMP theory, one feature of a GMP is the relative timing invariance, implying constant ratios of the durations of certain movement segments over a class of actions governed by this GMP. With regard to symmetrical bimanual aiming movements, it was found that especially MTs of both effectors were highly correlated. This led to the assumption that the movement duration of the two hands might be determined by a common motor program parameter (Schmidt et al., 1979). In general, bimanual movements with the same temporal structure are supposed to be coordinated easily, while movements with different temporal structures are not (Klapp, 1979). Thus, rapid bimanual movements might be controlled by one common underlying GMP (Heuer, Schmidt, & Ghodsian, 1995). However, contrary to the high temporal correlations of two limbs in bimanual movements, spatial characteristics of bimanual movements have not been reported to be strongly coupled (Schmidt et al., 1979; Sherwood, 1994), regardless whether symmetric or asymmetric bimanual movements were investigated. This observation led to the conclusion that temporal and spatial movement characteristics are controlled by different mechanisms (Heuer, 1986), or at least by common and specific motor program parameters (Schmidt et al., 1979). Moreover, the observation of clearly desynchronized temporal and spatial movement parameters after simultaneous onset in symmetrical movements led to the assumption that even bimanual symmetrical movements might be controlled by independent hand-specific neural processes (Boessenkool, Nijhof, & Erkelens, 1999). However, even when two limbs produce completely different spatiotemporal movement patterns, it can be observed that the concurrent activities influence each other. This phenomenon is referred to as “cross-talk” (Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). Cross-talk in bimanual movements with different amplitudes leads to amplitudes becoming similar, an effect that may be interpreted as an “assimilation effect”. Assimilation effects can be considered as evidence for single control units, i.e. bimanual movements can be presumed to obey one single GMP. This latter assumption is also based on the idea that different bimanual actions are difficult in the beginning, but with practice the performer constructs a new bimanual GMP that also leads to a tight linkage in time between the two movements (Schmidt, Heuer, Ghodsian, & Young, 1998). Thus, even asymmetric movements might be controlled by one GMP. Additional evidence for a unitary program governing multi-limb actions comes from the analysis of asymmetrical bimanual movements (Swinnen et al., 1991). Swinnen et al. investigated a human performer's capability to produce two different movement trajectories – a horizontal unidirectional elbow flexion movement and a reversal flexion-extension-flexion elbow movement – simultaneously. The authors found a tendency to synchronize the motor output pattern, i.e., two movements assimilated or adopted each others' characteristics, indicating that they were not executed independently from each other. On the muscular level, the authors found asymmetrical synchronization effects, which were interpreted as evidence for an apparent limitation of humans to do "more than one thing at a time with the upperlimbs" (Swinnen et al., 1991, p. 171).

Another view on the control of bimanual movements has been brought forward by Mechsner, Kerzel, Knoblich and Prinz (2001). These authors proposed that symmetric movements are facilitated when the perceptual goals are symmetric, independent of the muscle groups activated. In their experiments participants had to perform symmetric or parallel finger oscillation or tapping patterns with congruous or incongruous hand positions. It was found that instructed symmetrical oscillation or tapping patterns were always stable independent of hand position and thus independent of the activation of homologous muscles. Consequently, it was rather perceptual symmetry than muscle coactivation that decided the stability of the movement. On the other hand, instructed parallel oscillation or tapping patterns always tended to disintegrate and switch to symmetric patterns, i.e., there was a tendency to switch to perceptual symmetry instead of muscle coactivation. Thus, the control of the bimanual movement depended on perceived spatial symmetry, facilitating even "impossible" and highly complex movements. Therefore, bimanual motor control might be much more under perceptual-cognitive than under motor program control (Mechsner, 2004), especially when planning and execution of movements is assumed to be goal-oriented (for further examples see also Kunde & Weigelt, 2005; Mechsner & Knoblich, 2004; Weigelt, Kunde, & Prinz, 2006). Regarding steering wheel movements, the activated muscle groups of both arms are not homologous, but the perceptual goal – the direction of a certain lane change – is common to both. Since the point-symmetry of the steering wheel movement might lead more to the perception of symmetry than to the perception of asymmetry, a reversal steering wheel movement sequence might also be under perceptual-cognitive control.

Unfortunately, steering wheel movements have rarely been directly in the focus of empirical psychological research. One study by Davis, Cui and Spence (2008) investigated the speed-accuracy trade-off in a reciprocal aiming movement performed with a steering wheel. The corresponding typical finding in reciprocal aiming tasks consists in a linear relationship between the time required to move between two targets and the effective difficulty of that movement, also known as "Fitts' law" (Fitts, 1954). Davis et al. (2008) were able to show that Fitts' law also holds for rotational steering wheel movements. From this result the authors derive the assumption that steering wheel movements might obey the same rules as unimanual aiming movements and that reciprocal aiming may be a useful tool for the study of driving in laboratory settings. Apart from Fitts' law, the "Simon effect" for rotational wheel responses attracted some serious research (Guiard, 1983; Wang, Proctor, & Pick, 2003, 2007). The Simon effect basically holds that when stimuli occur in left or right spatial positions, but the stimulus location is irrelevant to the task, then spatially compatible reactions are facilitated in terms of reduced RT and increased accuracy (Simon & Small, 1969). With regard to Guiard's experiments (Guiard, 1983), Wang, Proctor and Pick (2003) conducted a series of three experiments. They examined clockwise and counterclockwise wheel rotations in response to high- or low-pitched tones that were presented either exclusively to the left or the right ear. They especially analyzed three different types of hand positions on the wheel: both hands at the top, at the middle or at the bottom of the wheel. They found positive Simon effects for the top and middle position – RT was shorter and accuracy was higher when the tone location corresponded with the left or right movement of the top of the wheel. Interestingly, this positive Simon effect could be transformed into a negative Simon effect, when participants held the wheel at the bottom and were instructed to move their hands into the required direction (instead of moving the wheel into the required direction). In this case, a hand movement to the left corresponds to a wheel movement to the right and vice versa, thus there is a conflict between two different reference frames. Since the experimenters were able to modulate the Simon effect based on the instructional goal, the study delivered evidence for the ideomotor principle: The action's goal was responsible for the Simon effect, but not the mere spatial arrangement.

Based on the short literature review in this section it seems to be reasonable to perceive a bimanual steering wheel movement as being controlled by one common process. In the more traditional view, this process could be called a GMP. From a rather modern perspective, the control of the bimanual steering movement might be facilitated by the adequate perceptual representation of the steering effect, i.e., by the movement's goal or by the response image (e.g. according to the ideomotor principle, Greenwald, 1970). The empirical section of this work will largely be based on the motor program metaphor, since the literature about response preparation also refers to the idea of "programming" movements (see section 1.2). However, the goal-orientedness of action planning as well as the integration of perceptual processes into the planning process will also be referred to, especially in the last experiment. Thus, both perspectives, the more motor-program oriented as well as the more cognitive goal-oriented perspective, will be considered. In both cases, response preparation – temporal as well as event-specific – was assumed to support information processing and bimanual movement execution, since the steering movement might be governed by a common process.

1.2 The Concept of Action Preparation

Each individual is in constant interaction with the environment. The individual's behaviour changes aspects of the environment and the environment's characteristics influence the individual's behaviour. Any expression of observable, or overt, behaviour therefore can be regarded as the result of antedating processes (Requin et al., 1991) rendering the individual capable of dealing with the immediate future. In our cognitive world the dimensions time and space are fundamental. The momentary situation can always be considered as a starting point for any action taking place at a certain place and a certain point in time, not far from now (Brunia, 1999). Anticipatory behaviour combines the present with the future and implies plans for action. As humans are able to learn from experience, they learn to anticipate future events and thereby adapt optimally to their respective environment. Anticipatory behaviour involves time estimations, i.e., the estimation of the time interval duration until a certain stimulus appears or a certain action has to be executed. "The aim of preparatory processes is to pre-activate certain brain structures during that interval in order to ameliorate the upcoming information processing" (Brunia, 1999, p. 214).

In many organisms motor reactions seem to be preprogrammed and to reflect a certain preparedness of the organism to its specific environment. Nevertheless even in primitive species processes of motor learning can be assumed in order to optimize its responses. Overt behaviour often consists of a serial chain of different actions, one action preceding and thus preparing the other: getting up to go somewhere, reaching out to grasp something or lifting something to put it somewhere. Any observable behaviour is preceded by covert, or non-observable, processes. Such covert processes enable human beings to time their behaviour or to adapt it to the specific demands of a situation with regard to aspects such as required force or accuracy. These preceding covert processes consist mainly of cognitive processes in nature, i.e., processes that are controlled by the CNS. One can assume that the effectiveness of these covert processes strongly influences the efficiency of any overt motor act.

One aspect of action preparation helps individuals deal with uncertainty. Motor preparation in this context is defined as "the processes by which the organisms are readied for perceiving future events and reacting to them" (Requin et al., 1991, p. 361). In this sense two theoretical poles of uncertainty delimiting a continuous spectrum in between can be distinguished. Either an individual is temporally and contextually fully informed about a certain required action or the individual is fully uncertain. In the first case a chronometric measurement of the reaction time (RT) to a certain stimulus would theoretically be zero as the individual would be perfectly prepared for its occurrence. In the second case it would theoretically be infinitely long as the individual would not even know how to react to the stimulus at all. Consequently an experimental approach to study the individual's uncertainty (which expresses a state of preparation) consists in measuring the individual's RT to a stimulus that requires a well-defined response. This type of stimulus is termed "imperative stimulus" as it "commands" the individual to react. In order to study preparatory processes the uncertainty about the occurrence and about the features of the imperative stimulus is experimentally varied by introducing a preceding stimulus that delivers some kind of information about the imperative stimulus. This preceding preparatory stimulus is termed a "precue", or "warning signal" (see Figure 2). The time interval between precue offset and imperative stimulus onset is named "interstimulus interval" (ISI) or, in the literature on temporal preparation, "foreperiod" (FP). As will be explained in section 1.2.2, the time from precue onset to the onset of the imperative stimulus, the so-called "stimulus onset asynchrony" (SOA), is of importance, too. The RT to the imperative stimulus is calculated from the onset of the imperative stimulus to the first occurrence of a certain response criteria such as a keypress, the detection of muscle activity in the EMG or the crossing of a relative/absolute criterion in a continuous reaction (e.g. force pulses). Any change in RT elicited by the variation of the precue or the FP is interpreted as an indicator of the efficiency of covert processes preparing the subsequent required response to the imperative stimulus. Thus, as already stated by Leonard (1958) the benefit of response preparation, understood as the planning and preparation of movements, is the reduction of reaction time (RT) to an imperative stimulus when preparatory advance information is previously available. This RT benefit is due to the reduction of uncertainty, since the preparatory advance information allows the individual to narrow his expectancy about the upcoming imperative stimulus to a certain degree (Requin et al., 1991).

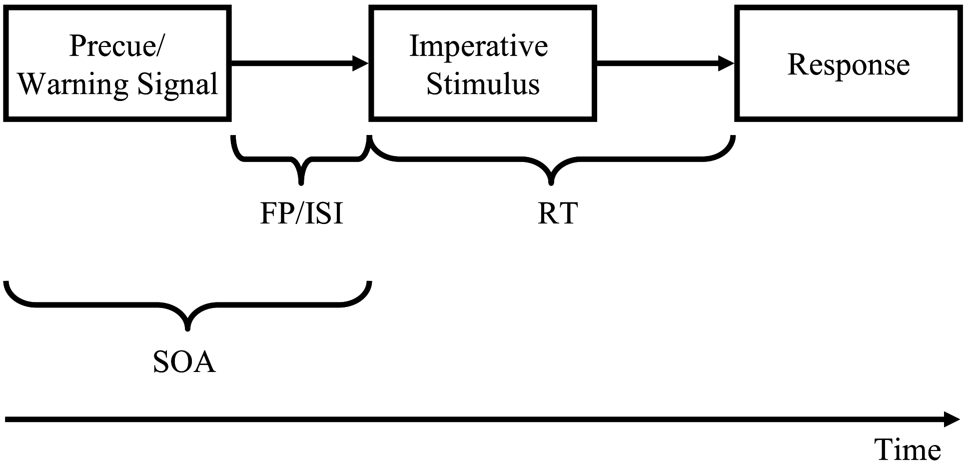

Figure 2: Basic scheme of an experimental trial designed to study the preparatory effects of a precue. FP: foreperiod; ISI: interstimulus interval; RT: reaction time; SOA: stimulus onset asynchrony.

According to Brunia (1999) two types of preparation for action can be distinguished. On the one hand "motor preparation" is achieved by telling the individual with the help of a precue about certain specific features of the response, so that the motor reaction can already be prepared (at least partially). On the other hand, "anticipatory attention" helps to optimize perception and thereby accelerates information processing. Anticipatory attention can be provoked by an unspecific precue that leads to a "waiting in readiness", i.e., a higher state of alertness. This distinction between both types is critical. First, it assumes motor preparation to be effective only in late information processing stages (e.g. response execution). Second, it implies the effects of anticipatory behaviour to lie exclusively in early stages of information processing (e.g. perception). Since these implications about the locus of effect have not been experimentally confirmed, Brunia's (1999) terms motor preparation and anticipatory attention seem to be slightly misleading. For this reason, the distinction between "event-specific preparation" and "temporal preparation" seems to be suited better to the purposes of this work. Event-specific preparation deals with the "event uncertainty" problem, i.e., the uncertainty about what reaction has to be executed (Requin et al., 1991). Temporal preparation deals with the "time uncertainty" problem and helps answer the question when a certain response is required. These two concepts have inspired a great deal of empirical research and can be considered well-established cognitive psychological concepts. None of these concepts per se implies a certain locus of effect in the information processing chain. In the next sections both concepts will be explained in more detail.

1.2.1 Event-Specific Preparation

Actions can be prepared more efficiently when a certain amount of information about the required action is available before response execution. Thus, the delivery of preparatory information before a certain action helps to study the event uncertainty problem (Requin et al., 1991). Moreover, the study of advance information effects on response execution allows investigations into how human information processing in terms of goal-oriented movement preparation affects human performance. In the next two sections two experimental paradigms, the movement precuing technique and response priming, will be reviewed.

Movement precuing. Already some decades ago it was shown that reactions to target stimuli can be speeded up by the presentation of advance information (Leonard, 1958). Based on the assumption that movements are prepared and controlled by motor programs, the most widely adopted experimental approach consisted in varying the response parameters (e.g. arm, direction or extent of movement) that are supposed to be included in the motor program (Larish & Stelmach, 1982) and to study the respective effects on RT. In this context the empirical and theoretical approach was extended by the provision of a powerful experimental paradigm to assess covert preparatory processes within the motor system, the so-called "movement precuing technique" (Rosenbaum, 1980, 1983). This technique is based on the experimentally structured manipulation of advance information given before the final response is required. Rosenbaum (1980) argued that if any partial information about one or several movement dimensions is available before the initiation of the movement, one, some, or all parameters of the motor program can be specified in advance. The more parameters are specified in advance the faster the movement can be initiated, since at the time of the imperative stimulus only the missing parameters have to be specified. In this respect the movement precuing technique is based on the idea of sequential information processing: RT is composed by the time needed to identify the imperative stimulus, the time needed to specify the missing parameters and the time needed to execute the response. The use of precues allows the elimination of the respective parameter specification time and its transfer before the reaction. This assumption is commonly termed "advance-specification assumption" (Heuer, 1988a). Further on, the additivity of programming times with the number of precued parameters leads to the assumption of serially processed programming operations in this paradigm. If shortening of RT only occurs when some parameters are precued simultaneously, then a serial order of the programming process can be inferred with one parameter being necessarily programmed before the other (Requin et al., 1991). In experimental practice the movement precuing technique is realized in the form of a modified choice reaction task in which an imperative stimulus requires a participant to perform a specific reaction as quickly as possible. The imperative stimulus is preceded by a precue that carries entire, partial or no information about the parameters of the forthcoming movement. The duration of the FP between precue and imperative stimulus is held constant. If the preparatory information is utilized then RT should be shorter with advance information than without it (Müller-Gethmann, Rinkenauer, Stahl, & Ulrich, 2000; Requin et al., 1991). Several studies support the idea of the advance-specification assumption (for a review see Müller-Gethmann, Ulrich, & Rinkenauer, 2003). These studies show that advance information typically yields faster and more accurate responses to the imperative stimulus. The corresponding reduction of RT is termed the "precuing effect".

Evidence for the precuing effect stimulated research about which stage of the human information processing chain is shortened most by movement precuing. According to the model view of Pashler (1984) and Pashler and Johnson (1989) information processing between perception of a stimulus and motor execution of a response can be regarded as a three-stage process (see Figure 3). First, the stimulus has to be perceived and identified (early perceptual stage), second a response has to be selected (central stage) and third, the response has to be executed (late motor stage). Following the ideas of Sternberg (1969) these stages were supposed to be discrete, i.e., exclusively sequential in nature.

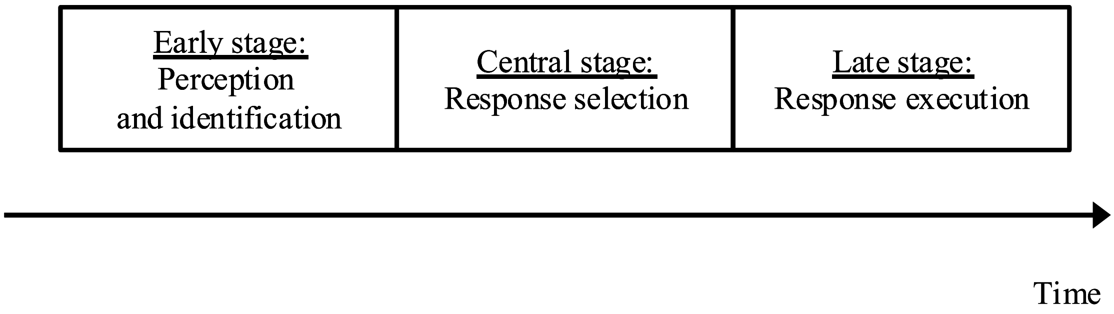

Figure 3: General model of sequential information processing.

In this context Goodman and Kelso (1980) criticized Rosenbaum's prevailing view that especially the late motor stage benefits mostly from event-specific precues. In general, the claim of Goodman and Kelso was that the precuing effect might be located in a central, premotor stage, namely the stage of response selection. Thus, the reduction of response alternatives by the deployment of precues would lead to a decrease in RT. This explanation corresponds to the findings of Hick (1952), who attributed reductions of RT in choice reaction tasks employing precues to the substantial reduction of response alternatives. In most cases each single information presented by a precue reduces this number of alternatives by half (Zelaznik, Shapiro, & Carter, 1982).

An approach to the solution of the debate about the locus of the precuing effect was made by Leuthold, Sommer and Ulrich (1996). In a psychophysiological study these authors employed the "lateralized readiness potential" (LRP) to bisect RT into premotor and motor stage. The results of this study pointed out that precues about the movement direction shortened late motor processes of the required response. However, RT and the amplitude of the LRP differed with regard to the number of precues. RT decreased with the number of precues, whereas the LRP amplitude only increased when the precues fully specified the response movement (Ulrich, Leuthold, & Sommer, 1998).

Additional arguments against the hypothesis of Goodmann and Kelso (1980) were delivered by Anson, Hyland, Kötter and Wickens (2000). These authors found differential effects of movement parameters on RT in spite of highly compatible stimulus-response conditions. They concluded that not only the number of parameters but also their type and characteristics influence response preparation processes. Moreover, precues specifying the required movement force lead to the shortening of the early stages of information processing (perception) and the central stages (response selection) (Müller-Gethmann et al., 2000).

These results support the view that different neuronal ensembles participate in specifying different movement parameters such as direction or force. In fact, Leuthold and Jentzsch (2001) were able to show that preparatory information about movement direction and movement hand was used in premotor brain areas. Processes that are run in the supplementary motor area and in the cingulated motor area possibly reflect the composition and selection of motor programs. The more parameters were specified before the imperative stimulus, the higher was the observed activity in those areas. The final implementation of a motor program in terms of muscle specific activity seemed to be attributable to the lateral premotor area and the motor cortex (Leuthold & Jentzsch, 2001).

Most precuing studies have been undertaken for aimed arm movements composed of ballistic and controlled movement parts. Direction and amplitude are considered as relevant parameters of a single arm movement that can be specified in advance (Bock & Arnold, 1992). Moreover, the parameters arm (in terms of left or right) and movement force can be specified before movement onset. However, it is unclear to which extent the duration of a movement can be programmed. In this context the “short-long” effect states that the programming of a long movement requires more time than the programming of a short movement, an effect that can be observed especially in choice reaction tasks (Klapp, 1974; Klapp, Wyatt, & Lingo, 1974). Spijkers and Steyvers (1984) transferred the short-long effect successfully to more complex movements. They also confirmed the hypothesis that movement parameters such as direction and movement duration can be programmed independently from each other. Vidal, Bonnet and Macar (1991) delivered evidence that even long lasting movements can benefit from advance parameter specification. According to their view the short-long effect is mainly a result of the amount of programming effort. These authors claimed that movements up to a duration of 2500 ms can be considered as programmable, without hierarchical dependence of effector side and movement duration.

A general critique of the advance specification assumption was brought forward by Heuer (1987b). The movement precuing paradigm is based on the assumption of sequential information processing. This assumption implies that each information processing step in each stage has to be terminated completely before the stage’s output can be delivered to the next stage, which in turn cannot start its processing earlier. In addition, identical reactions have to be assigned to both hands so that the spatial and temporal aspects of the required response pattern can be specified in advance. Such a preparation would not be possible if different reactions (such as e.g. “tapping” or “alternating”) were assigned to both hands. In this case, the specification of spatial-temporal movement parameters has to wait until the presentation of the imperative stimulus, at least when sequential information processing is assumed. Heuer suggests an alternative explanation for the advance specification assumption, namely the “programming interactions assumption”. This assumption is based on the idea of continuous information processing models in that any available information is directly transferred from one information processing stage to the succeeding one. This mechanism implies the possibility that alternative reactions can already be prepared during the processes of stimulus perception and identification. Thus, interactions between preparatory processes can take place so that for example similar reactions might facilitate each other whereas strongly different reactions might inhibit each other. Based on empirical evidence, Heuer states that it seems reasonable to assume that different models of information processing can be indicated in different situations (Heuer, 1987b, 1988a).

With regard to driving, one might assume that event-specific preparation takes place almost at any moment. Each driver extracts the necessary information for vehicle control and navigation from the environment and tries to anticipate future reactions. However, although the relevance of event-specific preparation for driving appears to be clear, the precuing technique has not been used in driving studies to date. For this reason, the movement precuing technique will be studied in an applied context: a lane change task. In a further step, it will be combined with temporal preparation in order to analyze possible interactions between temporal and event-specific response preparation.

Response priming. Another experimental approach that serves to study response preparation in terms of movement programming is provided by “response priming” methods (Larish & Frekany, 1985; Rosenbaum & Kornblum, 1982). In a response priming task a prime predicts a requested movement with high likelihood. This means helping the subject to prepare the required response. However, in a certain percentage of all trials the required response is different from the primed response so that the prepared response has to be altered. An important difference between response priming and response precuing is that the prime in the former technique always supplies complete information about the required movement, whereas the precue in the latter technique might supply full, partial or even no information about the response (Lépine, Glencross, & Requin, 1989).

In the response priming paradigm, a typical result consists in the so-called "validity effect". With regard to RT, this effect reflects much shorter RTs in trials when the priming stimulus predicts the upcoming response correctly (valid trials) compared with trials in which the priming stimulus conveys invalid information about the upcoming response. The RT lengthening in invalid trials is interpreted as the sum of times required to despecify and to respecify the movement dimensions for which the prime was invalid (Lépine et al., 1989). Moreover, the validity effect also implies that RTs in trials without movement-specific information are longer than RTs in valid and shorter than RTs in invalid trials (Larish & Frekany, 1985; Larish & Stelmach, 1982; Lépine et al., 1989; Leuthold, 2003; Leuthold & Jentzsch, 2001; Rosenbaum & Kornblum, 1982). It is generally assumed that the validity effect reflects time-consuming respecification costs that are produced by time-demanding parameter reprogramming processes (Larish & Frekany, 1985; Lépine et al., 1989; Leuthold, 2003). Reprogramming in this context is to be understood as the restructuring of an already constructed motor program when an unexpected response must be executed in its place (Larish & Stelmach, 1982). Contrary to the hitherto prevailing view that reprogramming costs are mainly motor costs, Leuthold (2003) showed in a LRP study that these reprogramming costs are located in pre-motor processing stages, so that perceptual and response selection processes presumably contribute to the validity effect.

For the validity effect to occur, a certain proportion of valid to invalid trials is required. The usual proportions range from 80%:20% (valid : invalid trials) (Larish & Stelmach, 1982; Sterr, 2006), over 75%:25% (Larish & Frekany, 1985; Leuthold, 2003) and 65%:35% (Lépine et al., 1989) to even 50%:50% (Crundall & Underwood, 2001). With regard to all experimental trials, valid and invalid trials usually make up between 50% and 100% of all trials, while the remaining percentage consists of neutral trials. As Low and Miller (1999) showed, the validity effect cannot be assumed to occur at any proportion between valid and invalid trials. These authors investigated the usefulness of partial information in a choice/nogo task. In this task, one stimulus varies on two dimensions, namely shape and size, and thus transfers information about the response hand and whether the response is to be made (go trials) or to be withheld (nogo trials). In go trials a LRP arises before response execution. This LRP allows monitoring the covert cognitive processing that occurs between the stimulus and the subsequent response. It can be regarded as an index of specific hand preparation. Crucial for the experiment of Low and Miller (1999) was whether the LRP would also be present in nogo trials, especially when the overall probability of a nogo trial was high. Three different proportions between go and nogo trials were analyzed, namely 67%:33%, 50%:50% and 25%:75%. Interestingly, no LRP activity was monitored in the condition with the highest nogo probability whereas reliable LRPs were measured in the two other conditions, indicating the most intense preparation in the condition with the highest go probability. The authors conclude that response preparation will only begin under circumstances in which that information has substantial utility in the task context.

With regard to a driving context these results can be interpreted in terms of usefulness of road sign or ADAS information. In an interesting study, Crundall and Underwood (2001) investigated the priming function of warning road signs in a repetitive as well as in a semantic priming context. Traffic signs pursue the purpose to facilitate motor responses for an upcoming required action and to reduce reaction time to subsequent hazards. Thus, reactions on traffic signs can be regarded as the perfect scenario for response preparation in an applied context. The authors used triangular warning signs (right-hand and left-hand bends, among others) as primes in two different conditions. In the semantic priming condition the primes were followed by a digital picture of a road scene clearly showing a bend to the right or left. In the repetitive priming condition the same digital picture was used, but the road signs that were also used as primes were additionally embedded in the picture. The road signs were used as primes that were either valid or invalid or neutral with regard to the target scene. The results showed a clear validity effect in the repetitive priming condition for experienced drivers, whereas novice drivers only benefitted from neutral trials and were slowed down in their reactions by valid and invalid primes. This effect was interpreted as evidence for the development of automated responses to road signs and other driving stimuli with growing driving experience, whereas novice drivers still had to cope with the novelty of the stimulus. In addition, experienced drivers also benefitted from valid primes in the semantic priming condition. As a general conclusion, Crundall and Underwood (2001) proposed that road sign information transmission is not only conscious but also automatic. Additional support for the idea of strengthening the priming function of road signs comes from Koyuncu and Amado (2008), who replicated and enlarged the findings of Crundall and Underwood with regard to stimulus location and stimulus duration.

With regard to ADAS, highly reliable ADAS with an almost perfect prediction of upcoming events would lead to the best driver support with regard to his level of response preparation, but at the risk of high preparation costs in the case of failure. On the contrary, ADAS delivering unreliable information in the driving context will not be taken into account by the driver as the system information will be regarded as useless. Since the response priming paradigm has proved to be a useful tool to study response preparation, in this thesis it will also be deployed in the lane change task. The question to be answered is whether the validity effect can be replicated in such an applied task and to which extent it might differ from the results of basic research. As will be concluded in section 1.4, the answer to this question is not trivial. Furthermore, the response priming paradigm might prove useful to estimate the costs of response preparation in an applied context.

1.2.2 Temporal Preparation

Temporal preparation leads to a higher state of readiness for the performance of reactions. This state of readiness seems to require at least 150 ms to be built up and the maintenance duration of this state seems to be limited to about 250 ms (Requin et al., 1991). The temporal preparation for a response is achieved by a precue that can be regarded as a temporal warning signal. It does not transfer any information about the required reaction characteristics. It only supports the anticipation of the temporal occurrence of the imperative stimulus. RT to the imperative stimulus is shorter in trials with a temporal warning signal compared with trials without a temporal warning signal, as was shown first by Woodrow (1914). According to Niemi and Näätänen (1981), the warning signal reduces the uncertainty about when the imperative stimulus will occur, which in turn promotes temporal preparation of the response. Thus, the warning signal helps to solve the time uncertainty problem (Requin et al., 1991). Interestingly, this effect is not restricted to a specific modality such as visuality but can also be observed for auditory stimuli and even in crossmodal stimulus situations (Müller-Gethmann et al., 2003). Although the temporal warning signal is not informative about the type of reaction, it also reduces RT in choice RT tasks (Simon & Slaviero, 1975).

The extent of RT reduction by adequate temporal preparation depends on the duration and the distribution of the FPs. The FP’s duration is defined by the length of the time interval between the offset of the temporal precue and the onset of the consecutive imperative stimulus (see Figure 4). With regard to the FP distribution in an experimental design, variable and blocked FP paradigms can be distinguished. In a variable FP paradigm, all FP durations are equally distributed across all trials and randomly presented. In this paradigm, the typical result consists in decreasing RTs with increasing FP durations (Bertelson & Tisseyre, 1968). That is, RTs are shortest when FP duration is longest. The decrease of RTs to a certain optimum is explained by the “foreperiod aging effect”. This effect claims that the conditional probability of the occurrence of the imperative stimulus increases with the length of the actual FP (Klemmer, 1956; Niemi & Näätänen, 1981). This increase in conditional probability leads to a growth of response preparation, so that participants will be well prepared for the moment of imperative signal onset which in turn promotes short RTs (Näätänen & Merisalo, 1975). In order to counteract the effects of aging FPs, the increase of conditional probability for the occurrence of the imperative stimulus has to be avoided, i.e., FPs have to be “non-aging”. One respective experimental approach consists in keeping the conditional probability of the imperative stimulus occurrence constant by varying the relative frequency of the precue and introducing blank catch trials (Näätänen, 1970). Another approach, especially for continuous FP duration distributions, has been proposed by Gottsdanker, Perkins and Aftab (1986), who distributed FP duration according to an exponential function. Nickerson and Burnham (1969) implemented a non-aging FP paradigm in which a binary random process (in analogy to a toss of a coin), repeated every 25 ms during the FP, decided on the occurrence of the imperative stimulus. The probability of the binary process to end the FP was biased and kept constant at each moment during the FP, so that no blank catch trials were needed. A final approach to approximate non-aging FPs, according to Niemi and Näätänen (1981), consists in expanding the FP duration systematically from the shortest to the longest FP duration. Also in this case increasing RTs with increasing FP durations can be expected (Hermelin, 1964), except for very short FPs. In a non-aging FP paradigm RT will be shortest with a medium FP duration and increase with shorter as well as with longer FP duration. First, increases in RT with very short FP durations are due to a certain minimum time interval required in order to built up temporal preparation (Bertelson & Tisseyre, 1968). Second, RT will not be shortest but can even be longest in the shortest FP, regardless of its absolute duration (Näätänen, 1970). The increase of RT that can be observed with FPs longer than the FP with minimal RT can be attributed to the increasing uncertainty about when the stimulus will be delivered. The according RT function of short, medium, and long FPs will therefore follow a U-shaped function (Drazin, 1961).

In case of blocked FPs (see Figure 4), i.e., when FP duration is kept constant across the number of trials in one experimental block, long FPs are associated with higher temporal uncertainty, since temporal preparation can only be optimally maintained for a short time period (Requin et al., 1991). This higher temporal uncertainty is reflected in prolonged RTs for long FPs (Klemmer, 1956; Näätänen & Merisalo, 1975; Niemi & Näätänen, 1981). Thus, in a blocked FP paradigm shortest RTs are achieved in the shortest FP condition provided that the shortest FP is long enough to reach the peak of optimal preparation, i.e., the highest state of readiness (Näätänen, Muranen, & Merisalo, 1974). An overall optimal FP length can not be determined, as it strongly depends on the general experimental setup (Teichner, 1954).

As a general difference between blocked and variably distributed FPs one can observe generally shorter RTs in the blocked FP paradigm (Bertelson & Tisseyre, 1968; Requin et al., 1991). Common to both the blocked and the variable FP paradigms is the sharp decrease of RT after short FP durations in the range of 0 to 150 ms (Bertelson & Tisseyre, 1968), usually attributed to immediate facilitation induced by the temporal precue.

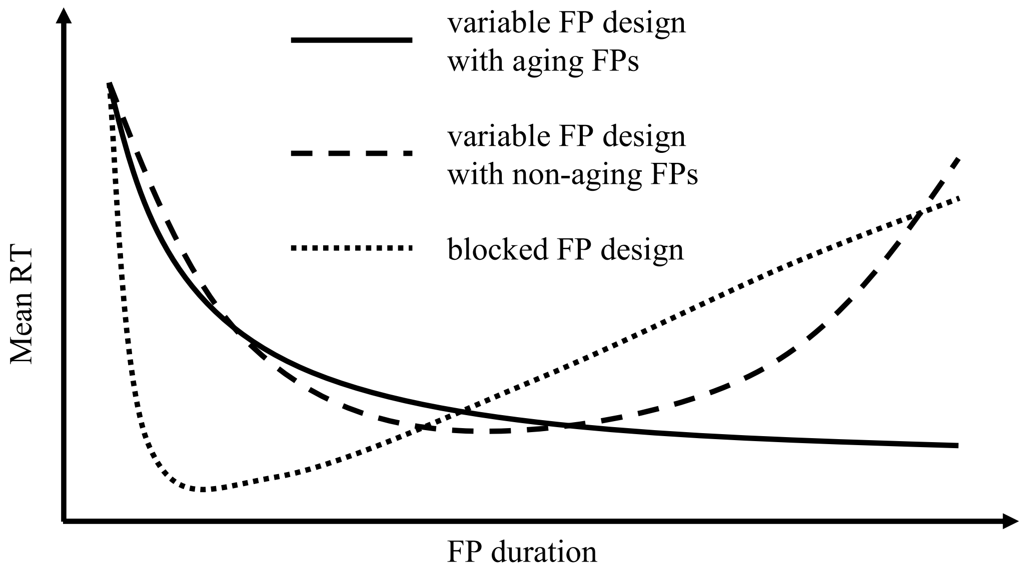

Figure 4: Schematic overview of mean reaction time (RT) as a function of foreperiod (FP) duration in variable and blocked FP designs.

Apart from the discussion about the general experimental design of FPs in an investigation of temporal preparation, Los and Schut (2008) asked which period should be regarded as the effective temporal preparation period. As was explained before (see Figure 2), the term FP typically denotes the time from warning signal offset to imperative stimulus onset, i.e., the ISI. It does neither consider the duration of the warning signal during which temporal preparation might already commence nor the duration of the imperative stimulus during which temporal preparation might still take place. In this context the SOA denotes the time from warning signal onset to imperative stimulus onset. As Los and Schut (2008) conclude the relevant time period – FP or SOA – seems to depend on the duration of the warning signal: Short signal durations seem to let temporal preparation start with warning signal onset, long signal durations seem to let temporal preparation start with warning signal offset. Consequently, the careful reader has to keep this set of difficulties in mind when studying the literature about temporal preparation, especially when interpreting figures and illustrations.

With regard to the sequential information processing chain, an ongoing scientific debate tries to isolate the locus of the RT effect elicited by temporal preparation. First it was assumed that mainly late stages (motor processes) were speeded up by temporal preparation (Sanders, 1980; Spijkers, 1990). These results were achieved by employing the additive factor method (AFM) proposed by Sternberg (1969). The AFM logic is based on the idea of sequential information processing, according to which stimulus information is processed serially in each of the three discrete stages: perception and identification, response selection and response execution. Certain characteristics of the stimulus as well as of the experimental design are supposed to execute their specific effects on one of these three stages. For example, the contrast of a stimulus to its background is assumed to influence the stimulus identification (Sanders, 1980). The combination of an experimental factor whose locus of effect is known with a second experimental factor whose locus of effect is unknown will lead to a pattern of RTs that allows inferences about the second factor's locus of effect. In case of an interaction between both factors the AFM assumes that both of them influence the same information processing stage. Since the locus of effect of one factor is always assumed to be known, the effects of the second factor can then be assigned to the identical locus. If the relationship between both factors is additive, the AFM assumes that both factors exert their respective influence on different information processing stages.

Additional studies looking for the locus of temporal preparation could subsequently show that also early and central stages of response preparation had a temporal benefit from temporal preparation (Los & Schut, 2008; Müller-Gethmann et al., 2003). Respective effects were attributed to the shortening of the early phase of response selection (Hackley & Valle-Inclán, 2003), late phases of perception or early phases of motor preparation (Hackley, Schankin, Wohlschlaeger, & Wascher, 2007). Even evidence demonstrating the potential shortening of early perceptual processes was collected (Correa, Lupiáñez, & Tudela, 2005;

Rolke & Hofmann, 2007). In view of this contradictory evidence, Correa et al. (2006) drew the conclusion that mainly the specific requirements of an experimental task determine the locus of temporal preparation effects.

Temporal preparation studies were usually conducted in the context of basic research questions. With regard to driving tasks there are not many studies available investigating the effects of temporal preparation. Only Nickerson, Collins and Markowitz (1969) concluded in their study of braking reaction time that temporal warning signals could be an effective means of decreasing RTs in an applied context such as driving. These authors also emphasized the need of experimental studies in applied contexts. In the introduction of Experiment 2 (section 2.3.1) this experiment will be described in more detail. Most other studies in the field of driving do not focus on the effects of temporal preparation but, for example, on the design and modality of warning signals (Roßmeier, Grabsch, & Rimini-Döring, 2005; Wolgalter, Conzola, & Smith-Jackson, 2002). A systematic experimental investigation of temporal preparation in an applied driving task has not been conducted so far. Therefore in this thesis temporal preparation in a lane change task will be studied in order to replicate basic evidence and to examine possible deflections.

1.3 Research in Driving

In the preceding sections it has become clear that the concepts of action preparation as well as the research about GMPs, action effects and kinematic movement properties have mainly been analyzed in basic settings. As a result, the experimental tasks deployed to analyze preparatory processes and kinematic characteristics were mostly reductionist in nature. This might be the reason why such concepts have not yet been transferred directly to more applied tasks, such as driving. Thus, up until know it has been unclear to what extent evidence from basic research, especially about action preparation, can be generalized to the field of driving research. Research in this field is mainly based on practical problems, often investigated directly in the field. But the use of driving simulators has been established since these systems have been shown to allow examinations of applied problems under controlled, economic and especially secure conditions. The next section will introduce some examples of simulated driving tasks.

1.3.1 Driving Simulations

The complexity of driving simulators deployed for research purposes varies considerably (Knappe, Keinath, & Meinecke, 2006). Fixed-base simulators cover a range from simple settings with a steering wheel and a monitor, over simulators with realistic controls and wide screen presentation up to high-end simulators including fully functional vehicle mock-ups and 180°-presentation. Dynamic driving simulators go beyond the possibilities of fixed-base simulators, as they simulate motion corresponding to rotational and translational degrees of freedom, thereby delivering sensory feedback about the driving dynamics. Of course, the required software varies accordingly between self-written code and commercial systems. It can generally be assumed that the degree of immersion of the simulator system increases with increasing system complexity (Loomis et al., 1999). The deployment of driving simulators for behavioural or design studies is attractive for different reasons. Simulators save time and development costs, and they do not expose participants to the concrete perils of road traffic. Most important for empirical approaches, experimental driving situations can be configured freely and repeated as often as necessary, so that comparable experiments can be run efficiently (Knappe et al., 2006). The main disadvantages of driving simulators arise from deviations between realistic and simulated perceptual stimuli (Kemeny & Panerai, 2003), which can even lead to simulator or cyber sickness (Mourant & Thattacherry, 2000). The costs of acquisition and maintenance as well as manpower requirements typically increase with increasing system complexity.

1.3.2 Driving Tasks and Research Areas

The use of driving tasks in human factor research has a long tradition. In 1943, during the Second World War, Otto Graf employed a driving task that resembled markedly modern driving simulations deployed nowadays (Graf, 1943). He used this task in order to analyze pharmacological influence on coordination. With the help of an endless milled ribbon he projected a curved route on the wall. His participants had to keep the shadow of a ball in the middle of the route with the help of a steering wheel and an accelerator pedal. He chose this method since he suspected the driving task to require high coordination performance and not to elicit feelings of monotony. In the following decades, different types of driving tasks have been established in experimental research (favoured by the rapid development of digital computing) in order to investigate associated perceptual, cognitive and motor processes.

The choice of a certain driving task is always determined by the research question behind the investigation. To better understand and improve the steering of curves, turn negotiation has been in the focus of many experimental studies (Land & Horwood, 1995; Land & Lee, 1994; van Winsum & Godthelp, 1996; Witt & Hoyos, 1976). Another classic simulator driving task is the car-following task, a so-called steady-state driving scenario. In this task the driver has to follow a leading car through a certain scenario and adjust the speed when the leading vehicle brakes or accelerates (Brookhuis & De Waard, 1994). This task structure allows for the controlling of the route and distance travelled in the simulator. In addition it introduces two simple dependent variables resulting directly from the scenario: headway to the leading car and braking reaction time when the leading car slows down (Horrey & Simons, 2007; J. D. Lee, Caven, Haake, & Brown, 2001).

Many simulated driving tasks serve to evaluate the impact of in-vehicle information systems (IVIS). The range of such systems is large, from collision warning systems and navigation aids to infotainment systems that enable drivers to conduct business while driving. A specific research question in this area concerns the effect of system alerts that shall prepare drivers for upcoming dangerous situations. A direct link from this applied research to the basic concepts of action preparation is obvious. So far, IVIS alerts have been studied in very naturalistic settings, i.e., in sophisticated fixed-base simulators delivering a realistic look-and-feel of the vehicle cockpit, the environment and the assistance systems. In these studies, the participants have to fulfil a certain driving task, e.g., driving on urban or highway settings (Cummings et al., 2007), and have to react to certain alerts whose characteristics are experimentally varied. Special attention has been given to the characteristics of auditory alerts such as auditory icon design (Graham, 1999), spatial location and symbolic meaning (Ho & Spence, 2005) and perceived annoyance and urgency (Marshall, Lee, & Austria, 2007). Common to these studies is the investigation of the impact of false alarms. The frequency of false alarms might undermine the alert effectiveness, since in the worst case the assistance systems will be ignored by drivers who feel annoyed by their dysfunction (Bliss & Acton, 2003). In general, studies about in-vehicle system alerts are more likely to link applied research to concepts and theories of attention, such as the model of multiple resources (Wickens, 2002) or cross modal links in spatial attention (Ho & Spence, 2005), than to link applied research to basic concepts of action preparation. Attention theories also play a major role in studies investigating complex aspects of driving. These attention theories include, for instance, constructs such as attentional overload (Matthews, Sparkes, & Bygrave, 1996), cognitive load (Y.-C. Lee, Lee, & Ng Boyle, 2007) or situation awareness (Ma & Kaber, 2005).

Many applied studies investigate driving as a whole, i.e., as the sum of its constituent functions. However, the more realistic the research setting is designed, the more difficult it is to make inferences about the functioning of basic processes – cognitive processes involved in action preparation, say – that constitute driving performance. Thus, for the purposes of this study, the level of analysis has to be lowered from a realistic demand to a rather reductionist, but still applied, level. Regarding the trade-off between experimental control and ecological validity (Loomis et al., 1999), experimental control will be increased whereas direct ecological validity will be decreased.

1.3.3 Control Processes Required in Driving

What is the difference between an applied and a reductionist driving task? Driving tasks vary in the level of requirements they demand from control and monitoring processes. The structuring of these levels of regulation has been a matter of scientific debate for some decades and has inspired different approaches. Seen from a general perspective, Rasmussen (1983) distinguishes three levels of human performance in man-machine interaction: skill-, rule- and knowledge-based performance. Basically, skill-based performance represents processes that take place without conscious control as automated patterns of behaviour. Rule-based behaviour can be seen as goal-oriented performance based on stored rules that result, for instance, from experience. Behavioural sequences on this level might follow a "cookbook recipe": a certain type of know-how is required but the action plan can still be followed step by step. Finally, knowledge-based performance reveals itself in unfamiliar situations for which no control rules are available. On this highest level, a plan based on the analysis of the environment has to be developed in order to solve the current problem. Another approach more specific to driving but still roughly corresponding to Rasmussen's general model (1983) was proposed by Michon (1985). This author described three levels of driving performance. On the lowest level, called operational, the driver is concerned with vehicle control in terms of motor responses, i.e., vehicle functions such as steering, braking, accelerating and so forth. On the second level, called the tactical level, the driver interacts with the surrounding traffic environment, i.e., with other road users. Actions belonging to this level include avoiding collisions, following the traffic rhythm and overtaking other vehicles. The third level, the strategic level, serves to plan the route (e.g., time demands, speed limits and choice of roads).

Another distinction of the processes required for driving, also based on three different levels of regulation, is offered by Horrey, Alexander and Wickens (2003). These authors describe lower-level activities required for vehicle control, such as the positioning of the vehicle in the lane as well as the control of vehicle speed. The second process consists of hazard awareness, i.e., the general understanding of the immediate environment. Finally, navigation is understood as a higher order task, including the route management to reach a certain destination. Only two levels of regulation were distinguished by Salvucci, Boer and Liu (2001). These authors described perceptual and motor processes – eye movements and steering movements, for instance – as belonging to the class of lower-level control processes. At the same time, monitoring processes required for steering a vehicle are considered high-level processes and comprise cognitive components such as situation awareness, navigational strategy, decision making and prioritization Moreover, high-level processes incorporate processes that are not primarily necessary for steering a vehicle, such as the management of action sequences, tuning the radio or talking on the phone.

From this short and certainly incomplete review of modelling man-machine interaction in the driving context, the common feature of all approaches becomes clear: All models distinguish between low- and high-level control processes, either in a two- or a three-level architecture. Consequently, realistic and applied driving tasks necessarily comprise such low- and high-level processes. However, the more basic a driving task gets, the more it focuses on low-level control processes, such as lane positioning, control of speed, eye and steering movements. But even a simple and reductionist driving task still requires a certain driver performance that is very different from, and much more applied than, a good portion of basic laboratory research tasks. The most intriguing characteristic of a driving task compared with a laboratory fundamental research setting consists in the continuous effort to keep the vehicle on route. Thus, a driving task typically belongs to the class of tracking tasks always requiring low-level control processes. Since tracking tasks demand complex sensory and motor performance, they have been deployed in basic psychological research for decades to investigate learning and maintenance of certain skills (Crossman, 1960; Trumbo, 1970; Trumbo, Noble, Cross, & Ulrich, 1965). In addition, simple driving tasks often serve as primary tasks in dual-task experiments, whereby a continuous driving task is supplemented by an additional task that typically increases the actual cognitive load and thereby renders the task more difficult (Cummings et al., 2007; J. D. Lee et al., 2001; Recarte & Nunes, 2000; Strayer & Johnston, 2001). Since additional tasks often introduce high-level monitoring and processing requirements as described in the preceding paragraphs, in the current study a simple, repeatable driving task is required without any additional secondary task. The main idea behind this choice was to impede any interfering influence on response preparation processes by high-level control processes. Since response preparation mainly focuses on the preparation of motor responses and, to a much lesser extent, on the preparation of decision-making, route planning and problem-solving, the driving task had to focus on low-level control processes. The following section introduces the lane change task that was chosen as a basis for the empirical work.

1.3.4 Lane Change Tasks

A lane change can be considered as a daily routine driving maneuver. Contrary to the car-following task, a lane change maneuver belongs to the class of tactical control tasks because drivers have to maintain appropriate safety margins around themselves instead of only reacting to the leading vehicle (Horrey & Simons, 2007). Despite their presumed simplicity, lane changes have received experimental investigation for many decades (e.g. Godthelp, 1985; Salvucci & Liu, 2002; Salvucci, Liu et al., 2001). One focus of actual lane change studies lies in their safety relevance, as lane changes can be regarded as causal factors for accidents (Underwood, Crundall, & Chapman, 2002). Several related aspects that influence the frequency of accidents have been investigated, such as the effects of rear mirror design (Luoma, Sivak, & Flannagan, 1995), the visual search behaviour of novice and experienced drivers (Underwood et al., 2002) and the lateral visibility out of the vehicle cabin (Sivak et al., 2006). The practical relevance of lane-change maneuvers for vehicle development is also reflected by the standardization of a double lane change maneuver that serves to evaluate and compare the characteristics of vehicles through objective parameters such as roll angle, roll rate, yaw rate and lateral acceleration (see ISO TR-3888-1).

In another approach the lane change maneuver is used as a prototypical driving task in order to analyze perceptual, cognitive and motor processes in driving. As was stated before, lane change tasks can be understood as permanent tracking tasks. Godthelp (1985) proposed that the steering of lane changes mainly requires closed-loop steering processes, whereby permanent visual control is required in order to correct for upcoming errors. Nevertheless he acknowledged that driving might not be an exclusive closed-loop process, but that additional open-loop processes might be operative. Accordingly, empirical research should also investigate open-loop processes so as to develop an understanding of how a lane change is controlled. The contribution of open- and closed-loop processes to successful lane change steering is the topic of an ongoing scientific debate (Cloete & Wallis, 2009; Godthelp, 1985, 1988; Hildreth, Beusmans, Boer, & Royden, 2000; Salvucci & Liu, 2002; Salvucci, Liu et al., 2001; van Winsum, de Waard, & Brookhuis, 1999; Wallis, Chatziastros, & Bülthoff, 2002; Wallis, Chatziastros, Tresilian, & Tomasevic, 2007).

Recently, Mattes (2003) introduced a PC-based driving simulation for a highly standardized "Lane Change Task" (LCT, see also Mattes & Hallen, 2008). It has been designed especially for secondary task evaluation (e.g. Engström & Markkula, 2005; Harbluk, Burns, Lochner, & Trbovich, 2006; Wilschut, Rinkenauer, Brookhuis, & Falkenstein, 2008). With this task, the impact of additional tasks on driving can be examined. The main driving task consists in steering a virtual vehicle on a one-way road with three lanes. Traffic signs alongside the road indicate lane changes to another lane. The driver is required to react as soon and as appropriately as possible to these signs. The mastery of the primary task can then be challenged by secondary tasks such as talking on the phone, tuning the radio, navigation or visual search tasks so that a dual task scenario can be approximated. The LCT's experimental output is measured by dependent variables focusing on the quality of lane keeping and steering. According to Knappe et al. (2006) the quality of lane keeping can be operationalized by the lateral position error (Cunningham, Chatziastros, von der Heyde, & Bülthoff, 2001), the average lateral position, lane deviations, or more elaborate measures such as time to line crossing (Godthelp, Milgram, & Blaauw, 1984). The quality of steering can be evaluated by the standard deviation of the steering angle, the number of zero crossings of the steering angle or the steering wheel reversal rate (Knappe et al., 2006). The advantages of the applied LCT by Mattes (2003) consist in a realistic graphical scenario and the continuous requirement of low-level driving processes, i.e., keeping and changing lanes. On this basis, additional tasks requiring high-level processes can be easily introduced and analyzed. With regard to the trade-off between ecological validity and experimental control (Loomis et al., 1999) Mattes' LCT represents a good compromise between applied as well as basic research requirements.

In the context of Mattes' work, the LCT was conceived as a primary task allowing the evaluation of additional tasks. With regard to the aim of this study – the investigation of action preparation in an applied driving task – the lane change maneuver itself is relevant. A task that requires continuous lane keeping and repeated lane changing without interferences from secondary tasks, traffic or situational changes in the environment can be considered a mostly low-level control task. For the current study, it is assumed that such low-level lane change steering movements can be prepared temporally as well as event-specifically. Since high-level processes such as navigation, prioritization or situation awareness might act as confounding factors in such a steering task, these processes were reduced as much as possible in the experimental tasks.

1.3.5 Head-Up Displays

HUDs project information directly into the forward field of view of an observer. The basic HUD technology has been developed by the aviation industry and was deployed for the first time during the second world war in American military planes (Ververs & Wickens, 1998). The technology transfer from aviation to the automotive industry led to the implementation of HUDs in vehicle cockpits. Thus, apart from the use for decades in aviation, an actual trend in vehicle design is the increasing deployment of HUDs in the driver's cockpit. Navigational data, speed, on-board vehicle computer output, ADAS information and comparable data can be pictured on a semi-transparent display of approximately 10 x 5 cm, located in the lower part of the windshield. The display's luminance is typically adjusted according to the ambient lighting conditions. Progress in projection technology, freely programmable content as well as increasingly available digital data from the vehicle periphery render the deployment of HUDs a reasonable alternative to classical HDDs (Wascher et al., 2005).

The main purpose of HUDs is "to obtain display information, with attention maintained on important events in the outside world" (Ward & Parkes, 1994, p. 703). This aim is assumed to be achieved by a reduction of reaccomodation time between HUD information and elements in the environment. The benefit of an HUD is attributed to its position in the forward field of view and the larger distance to the observer's eye compared with conventional HDDs. As suspected, the display position influences the driver's visual attention, since HDDs provoke gaze shifts between the display and the environment, leading to reaccomodation processes and changes in convergence. It seems to be evident that, in contrast to an HDD, an HUD reduces the cognitive effort for reading the displayed data, since the driver can let his eyes fixed to the distant environment, thus reducing eye accommodation and vergence effort as well as head and eye movements. Therefore, it is generally assumed that in an HUD condition RTs to relevant events in the environment will be shorter than in a comparable HDD condition. This advantage is termed reduction of visual scanning costs (Ward & Parkes, 1994). According to the model of multiple resources for task performance (Wickens, 2002) it is assumed that vehicle displays require attentional resources for foveal as well as for peripheral sight. When a task requires competing resources for foveal sight (e.g. reading a display while monitoring the environment), the main factor influencing the competition costs with regard to the display position is the distance between the display location and the environment. Consequently, the costs will be lower for an HUD than for an HDD. Evidence for the reduction of visual scanning costs with regard to aviation was delivered by Martin-Emerson and Wickens (1997) who confirmed that pilot performance in landing approaches was better with information display in an HUD than with that in an HDD. Horrey, Alexander and Wickens (2003) found that RTs to a secondary task in a dual task driving scenario increased in an HDD condition over that of an HUD condition.

However, there is also evidence that the advantages of HUDs over HDDs in vehicles are negligible from an ergonomic point of view. Kloke (2005) derived from physiological data that the decrease in eyes-off-the-road and accommodation time caused by HUDs might add up only to 100 ms compared with traditional HDDs. This difference is assumed to be marginal with respect to traffic safety. In a follow-up study Kloke, Jaschinski and Rinkenauer (2007) were able to further strengthen this argument. These authors measured the vergence dynamics during fixation changes in HUD and HDD situations by instructing their participants to make gaze changes between traffic and instrument positions. They found that the differences of vergence velocities between HUD and HDD were generally small and not decisive for ergonomic recommendations. In conclusion the human vergence and accommodation systems seem to be well prepared to deal with the conventional HDD position in a vehicle. Nevertheless, these authors mention the possible ergonomic advantages of HUDs for older drivers, since the accommodation capacity typically decreases with a longer lifespan. This assumption corresponds to the findings of Wilschut (2009), who showed that elderly drivers are less vulnerable to making errors in complex visual search tasks while driving when these search tasks are presented in an HUD compared with an HDD.

The use of HUDs in the current study is an attempt to minimize the number of potential confounding factors, such as eye-movements and changes in accommodation (cf. Ward & Parkes, 1994). Although ergonomically not necessarily relevant, these latter processes typically lead to increases in RT, as when, for instance, information is presented in an HDD instead of in an HUD (Horrey & Wickens, 2004). The potential inhibition of response preparation processes by suspected shifts in attention induced by HDDs (Ward & Parkes, 1994) should be avoided. In addition, lane-keeping by peripheral vision appears to be less affected by displays in a head-up position than in a head-down position (Summala, Nieminen, & Punto, 1996). For these reasons an HUD was assumed to be more suitable to study response preparation processes in driving than an HDD.

1.4 Experimental Outline and Study Aims

Two fields of research have been reviewed in the introductory sections. First, basic research has been carried out on action preparation and on basic mechanisms describing the production and control of movements. Second, applied research has been conducted about driving, often combining driving tasks with the investigation of theoretical constructs such as cognitive load, situation awareness (Endsley, 1995) or cognitive tunnelling (Wickens & Long, 1995). Although anticipatory behaviour is very natural in driving, it is striking that there are virtually no studies investigating response preparation in driving. Especially with regard to the concept of situation awareness, the concept of response preparation seems to logically fit into applied research. According to Endsley (1995), situation awareness is defined as the perception of elements in the environment, comprehension of the current situation and the projection of future status and dynamics of these elements. Given that response preparation can be understood as a process dealing with the immediate future and uncertainty (Requin et al., 1991) and helping the individual anticipate future events, this process can be understood as one of the mechanisms that might modulate situation awareness. It simply prepares the individual to cope more effectively and more efficiently with the actual driving situation. However, it can be considered an open issue to what extent covert movement preparatory processes can be revealed in a dynamic continuous driving task that is much more complex than a static laboratory task with discrete reactions. Driving requires permanent low-level and high-level processes to control the vehicle (Salvucci, Boer et al., 2001). Low-level control processes are required for tracking (e.g. lane keeping and curve negotiation) and monitoring of the environment (e.g. eye movements and attentional processes). High-level control processes serve to maintain situation awareness, to determine navigation strategies, or to manage additional tasks, such as tuning the radio or talking on the phone. Since all these processes demand cognitive resources, it is not trivial to assume that basic processes of temporal and event-specific response preparation can be isolated in an applied driving task. Consequently, it is unclear to what extent the evidence gained from mostly basic experiments can be generalized to driving.

For these reasons, this thesis aims to study the differential effects of response preparation in an applied driving scenario. This aim shall be reached by transferring basic experimental paradigms of action preparation into an applied but reductionist driving task: a lane change task employing HUDs for information transmission to the driver. The series of experiments conducted in the laboratory for virtual reality comprises RT as well as MT studies.

The specific objectives and experiments of this thesis are (see Table 1 for an overview):

1) The first aim of the study was to develop a specific lane change task that allows implementing basic cognitive experimental paradigms, such as event-specific and temporal preparation. However, the task characteristics had to be designed such that they resemble an applied driving task. The ecologic validity of the task still had to be obvious, so that the experimental results could be linked to human performance in driving.

2) The effects of event-specific preparation in a lane change task should be investigated. The aim was to show the applicability of the movement precuing paradigm to a driving task and to replicate basic research findings (Experiment 1). Kinematic properties of steering should be analyzed depending on the status of preparation. It was assumed that movement execution, not only cognitive processes, might be affected by advance information.

3) The effects of temporal preparation in a lane change task should be analyzed in order to find out if they are comparable with the results of basic research (Experiment 2). Kinematic analyses of the steering wheel movement were performed to compare the kinematic effects of temporal preparation with those of event-specific preparation.

4) A combined approach of temporal and event-specific preparation in basic research is rarely found (Requin et al., 1991). It is generally unclear to what extent interactions between both processes affect human performance. The third experiment should be based on the

findings of Experiment 1 and 2 and answer to what extent both preparatory processes exert a common influence on lane change performance. As will be explained later, an additional fourth experiment was conducted combining temporal and event-specific preparation in order to deal with open issues resulting from the preceding experiments.

5) One additional basic research paradigm, namely the response priming paradigm, should be implemented into the lane change task. Two ideas stood behind this fifth experiment. First, a successful test of another basic research paradigm provides an impression of the generalizability of the preparation concept. Second, this experiment can be considered an initial approach to the investigation of negative effects of preparation in driving, since the validity effect represents the costs of preparation. It should open a wider perspective on preparation by focusing on its negative consequences. This scenario mostly resembles the investigation of false alarms in realistic driving tasks.

6) After having studied the original effects of temporal and event-specific preparation as well as of response priming, these basic concepts should be transferred to a more applied research question: the design aspects of conformal HUDs. Spatial depth is a parameter that can be considered as characteristic of conformality. The question to be answered in this context was the extent to which the HUD's spatial depth affects cognitive information processing (Experiment 6) and if it might also support the process of action preparation (Experiment 7). To this end, the concepts of temporal and event-specific preparation were varied to prove their usefulness for a more applied context.

Table 1: Experimental outline of this thesis.

Exp. No.	Experimental paradigm	Main research question
1	Event-specific preparation	Replication of precuing effect, analysis of kinematic properties and enhancement of basic findings.
2	Temporal preparation	Replication, analysis of kinematic properties and enhancement of basic findings.
3	Temporal and event-specific preparation	Investigation of a possible interaction between both (temporal and event-specific) types of preparation.
4	Temporal and event-specific preparation	Investigation of a possible interaction between both (temporal and event-specific) types of preparation.
5	Response priming	Replication of validity effect and enhancement of basic findings, potential negative effects (costs) of preparation on lane change performance.
6	Event-specific preparation	Influence of the HUD's spatial depth on cognitive processing.
7	Adaptation of event-specific preparation, temporal preparation	Influence of the HUD's spatial depth on event-specific preparation.

2 Empirical Work

In the following empirical section the experimental work is described. Since there are several methodological aspects common to all experiments these similarities are pointed out first. Unless specified otherwise in the respective methodological sections of each experiment, the methodological details were as presented in the general method section.

2.1 General Method

Each of the experiments was based on a lane change task. Lane changes were prepared temporally, event-specifically or by response priming. The experimental sessions lasted between 2 and 2½ hours. Participants were always supervised by an investigator.

2.1.1 Participants

Participants in all experiments had to be at least 18 years of age. Prior to their participation, informed consent was obtained from all participants. A valid driving license was required. All participants were screened for normal colour vision with the Ishihara Test for Colour Blindness (Ishihara, 1990) and for normal stereoscopic vision with the TNO Test ("TNO Test for Stereoscopic Vision", 1972), a random dot stereo test. The criterion for passing the Ishihara Test for Colour Blindness was set to at least 13 correct answers among the first 15 colour plates. To pass the TNO a minimum stereo acuity of 60 arc seconds was required. Participants were unaware of the study's purpose. They were either paid for their participation (8€/hour) or received course credits.

2.1.2 Driving Task, Apparatus and Stimuli

The experimental driving task was derived from the LCT proposed by Mattes (2003). The author of this thesis programmed a modified lane change task and implemented the simulation environment in C++ by making use of the WorldToolKit (WTK) as well as of standard libraries and compilers (for a general overview see Appendix B: General Program Flowcharts). Whereas Mattes' LCT comprises a road with only three lanes, in the current task several straight lanes beneath each other were implemented (see Figure 5). Due to this enhancement it became possible to allow many lane changes in the same direction without leaving the road. Thus participants could never expect the direction of the upcoming lane change due to a limitation of lanes. Participants drove with constant speed (approximately

60 km/h) in the middle of a freely chosen lane throughout the entire experiment and had to react as fast as possible to HUD-like imperative stimuli indicating the direction of upcoming lane changes. The appearance of the imperative stimuli was always announced by temporal or event-specific precues or primes. Constant speed was required in order to reduce the requirements in longitudinal control.

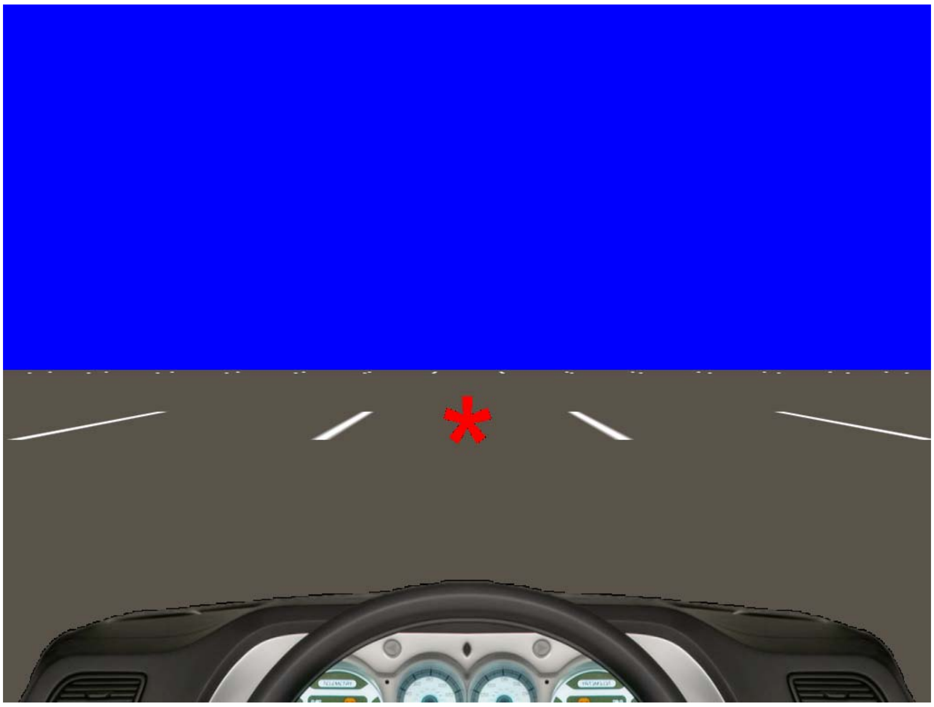

Figure 5: Sample view on the multi-lane road displayed in the fixed-base driving simulator. The red star represents a temporal precue.

The experiment was conducted with a fixed-base simulator that comprised a steering wheel mounted on a table and a Virtual Reality (VR) driving environment (see Figure 6 and Figure 7). The VR driving environment was presented by stereoscopic projection (frame rate: 120 Hz) on a large translucent screen (BARCO Baron Back Projection System). The driving task was run on a normal IBM compatible PC with enhanced graphics system. Thus, the driving environment and the HUDs could be perceived in virtual three-dimensional space. The resolution of the projected image was set to 1024 x 768 pixels. The participants were seated in a normal office chair in a viewing distance of 160 cm in front of the middle of the projection screen. The resulting field of view had a visual angle size of 45.90° × 35.20°. Participants could comfortably grip the steering wheel mounted on a table in front of them. They wore shutter-glasses (Crystal Eyes) throughout the entire driving experiment. Ambient light was kept low. Driving data was recorded with a frequency of 120 Hz and contained the following variables: trial number, time, x-, y- and z-coordinates of the actual position, steering wheel angle, heading angle as well as codes for the different tasks and events.

Figure 6: Photo of the experimental setup in the virtual reality laboratory.

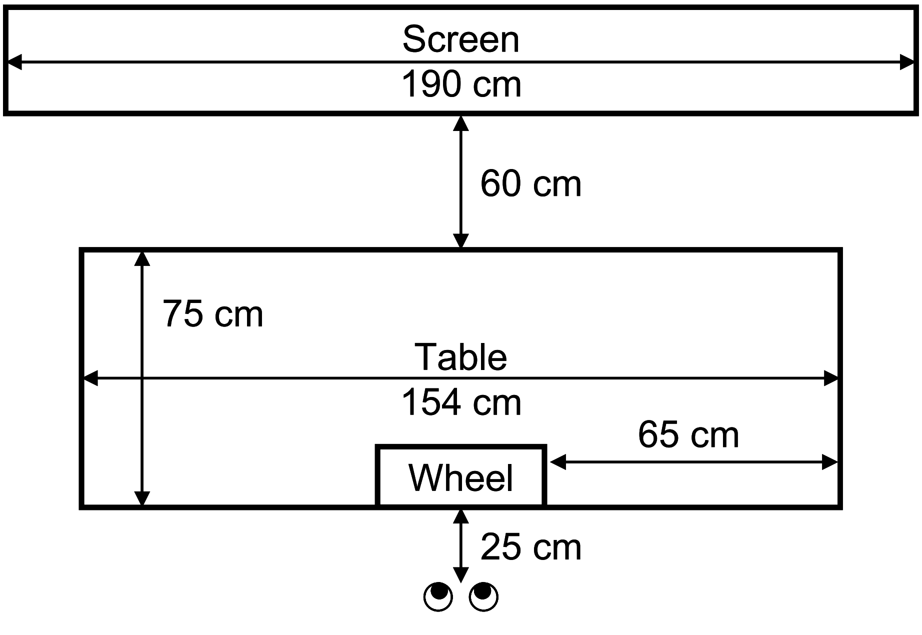

Figure 7: Schematic view from above on the experimental setup in the VR laboratory.

All stimuli were presented in an HUD-like fashion (see Figure 5). Disparity of the HUD corresponded to a distance of approximately 2 m in front of the virtual front windshield. The HUD appeared superimposed on the roadway. Stimuli were presented vertically approximately 7° below the horizon line (Gish & Staplin, 1995). Blue (11 cd/m^2) sky was presented above the horizon. Below the horizon line the gray roadway (6 cd/m^2) filled the screen. The road was made up of several straight tracks separated by white intermittent road markings (40 cd/m^2). The breadth of a lane corresponded to 20 geometrical units in the WTK geometry. Precues or primes were generally presented in red (RGB 255, 0, 0, 23 cd/m^2), whereas the imperative stimuli were presented in green (74 cd/m^2, RGB 0, 255, 0).

2.1.3 Procedure

Each participant was first informed about the general outline (duration, payment conditions, technical equipment, anonymity of data, potential health risks) of the experiment and the driving task before giving written informed consent. Then stereoscopic ("TNO Test for Stereoscopic Vision", 1972) and colour vision (Ishihara, 1990) were tested and general variables such as age, handedness, occupation and driving experience were collected. Afterwards the respective experimental task was explained and participants were familiarized with the driving task and the steering wheel. Prior to starting the experimental session, the participants were given training blocks from the respective experimental trials. Training blocks were discarded from data analysis.

In the event of reactions before the appearance of the imperative stimulus, of anticipated reactions (RT < 150 ms, RT will be defined in section 2.1.4), of lane changes in the wrong direction, of lane changes by more or less than the indicated number of lanes or of reactions that were too slow (RT > 1,000 ms) the participant received an error message as a reminder to react in time or to stay in the proper direction or to change by the indicated number of lanes. The error message could be cancelled by the participant by pressing a key on the PC keyboard positioned beneath the steering wheel on the table.

2.1.4 Data Reduction and Data Analysis

Reaction times. The steering wheel angle signal was filtered with a second-order dual-pass Butterworth-filter with a low-pass-cutoff of 8 Hz. The first derivation of the steering wheel angle (the velocity of the steering wheel movement) was calculated with a three-point-algorithm. RT was defined as the time from the onset of the imperative stimulus to the moment in time at which the steering wheel velocity of the first submovement reached 10% of its peak velocity. This point was identified by searching backwards from peak velocity to the last value larger than the criterion. A RT criterion based on steering wheel velocity instead of the steering wheel angle was chosen in order to counteract the potentially detrimental effects of drifting. Drifting encompasses a fixed steering wheel angle slightly different from the straight steering wheel position (0°) that also leads to a steady but not very dynamic lateral displacement. However, since the aim of the study was to analyze dynamic steering wheel movements, it was assumed that a velocity-based RT criterion would be better suited to capture the movement's dynamics.

As was pointed out, the RT criterion was relative. In response force studies, the typical RT criterion for response force is based on an absolute threshold (e.g. Mattes, Ulrich, & Miller, 2002; Müller-Gethmann et al., 2000; van der Lubbe, Los, Jaskowski, & Verleger, 2004). In these experiments, the response consisted of highly trained single finger keypresses, finger extensions or finger flexions. The simplicity of the movements as well as the highly trained movement execution reflect a certain standardization of these movements. However, with regard to the steering wheel movements examined in this thesis, such premises were not in place. In fact, it was expected that the steering wheel movement might be quite variable and individual. This assumption is due to the fact that the three lane change submovements required for the entire lane change were not restricted in any form so that any participant was allowed to execute each lane change maneuver quite differently from the preceding one. For this reason the relative velocity criterion was chosen in order to standardize the individual movements. Relative criteria that aim to detect the onset of a certain signal are deployed in ERP research, among other areas (Kiesel, Miller, Jolicoeur, & Brisson, 2008; Mordkoff & Gianaros, 2000). In kinematic studies, i.e., the analysis of movement trajectories, the determination of movement onset might also be derived from relative criterions applied to the velocity profiles of the movement (Boessenkool et al., 1999; Grosjean, Zwickel, & Prinz, 2009; Rand & Stelmach, 2000). However, absolute criterions are frequently deployed as well (see e.g. Sülzenbrück & Heuer, 2010).

It should be noted that a relative RT criterion might lead to difficulties when interpreting respective RT results. One could assume that different experimental conditions might not only vary in terms of RT but also in terms of peak velocity reached during the initial steering wheel submovement. In this case a relative criterion might systematically over- or underestimate RTs in a certain experimental condition. For this reason the RT calculation based on a relative criterion was counterchecked in the first two experiments with an absolute

RT criterion. This absolute criterion was also based on steering wheel angle velocity and was set to 10°/s. As was found in these two experiments (see Appendix A: Alternative and Additional Calculations), the comparison of the RT pattern based on the absolute criterion with the RT pattern based on the relative criterion did not show any marked differences with respect to the relevant factors for response preparation, i.e., for the event-specific or temporal precue factors. Consequently, the relative criterion was employed further on.

Errors. Only trials with correct responses were included in the data analysis. Trials in which participants responded before imperative stimulus onset, trials with RT < 150 ms (anticipations) or RT > 1000 ms (misses) (Correa et al., 2006), and trials with a wrong direction or wrong number of changed lanes were regarded as erroneous and discarded from RT and kinematic data analysis. However, error rates were arc-sine transformed in order to deal with the non-normality of proportions (see Winer, 1971), and they were analyzed and reported when the corresponding cell frequencies were meaningful.

Kinematic properties. In the literature, lane changes have been characterized according to their respective phases. Fragmentation approaches based on the position of the steering wheel lead to three or four lane change fragments (Godthelp, 1985; van Winsum et al., 1999). Another approach that considers the number of consecutive turns results in two lane change fragments (Macuga, Beall, Kelly, Smith, & Loomis, 2007). For the purposes of this thesis it seemed most adequate to characterize the fragments of a lane change according to the entire required steering wheel movement. This steering wheel movement resembles a sequence of almost reciprocal submovements rather than a simple aiming movement. The steering response consists of three submovements (see Figure 8): A first submovement (Figure 8: [t_1, t_3]) serves to leave the actual lane and to change the heading of the vehicle. The second submovement (Figure 8: [t_3, t_5]) into the opposite direction is necessary in order to reorient the vehicle heading back into the original straight heading. Finally, the third steering submovement (Figure 8: [t_5, back to baseline]) redirects the wheel back into the neutral middle position. This fragmentation into three submovements is based on an ideal and continuous execution of the lane change (Godthelp, 1985; Salvucci, 2006; Salvucci & Liu, 2002). It is characteristic of this entire steering wheel movement that each submovement (except the first one) has to be executed into the opposite direction of the preceding submovement. The change in rotation direction was used as a marker to separate the entire lane change steering wheel movement into its three submovements. However, preliminary data analysis revealed that no reliable criterion for the ending of the third steering wheel submovement could be defined. This confirms the observation reported by Salvucci and Liu (2002): Drivers reliably executed the initial and second steering wheel submovement and thereby roughly reached the target lane but then continued with a sequence of smaller sine-wave shaped maneuvers in order to adjust the vehicle position in the middle of the lane. Thus, these adjustment movements could neither be reduced to one single submovement nor be distinguished from the ongoing process of lane keeping between the trials. That is why the kinematic analyses in all experiments had to be restricted to the first two steering wheel submovements.

As illustrated in Figure 8, each steering wheel submovement was separated by its peak steering wheel velocity (PV) into a first accelerative (time to peak velocity, TTP) and a second decelerative (time after peak velocity, TAP) phase. TTP might be considered a ballistic phase prepared in advance, whereas TAP might be considered a controlled phase under closed-loop visual control (Beggs & Howarth, 1970; Carlton, 1981; Chua & Elliott, 1997). Such a phase separation is a common approach in the analysis of movement kinematics (Lajoie & Franks, 1997; Mieschke, Elliott, Helsen, Carson, & Coull, 2001). Each phase duration (TTP, TAP) for each respective submovement served as a dependent variable.

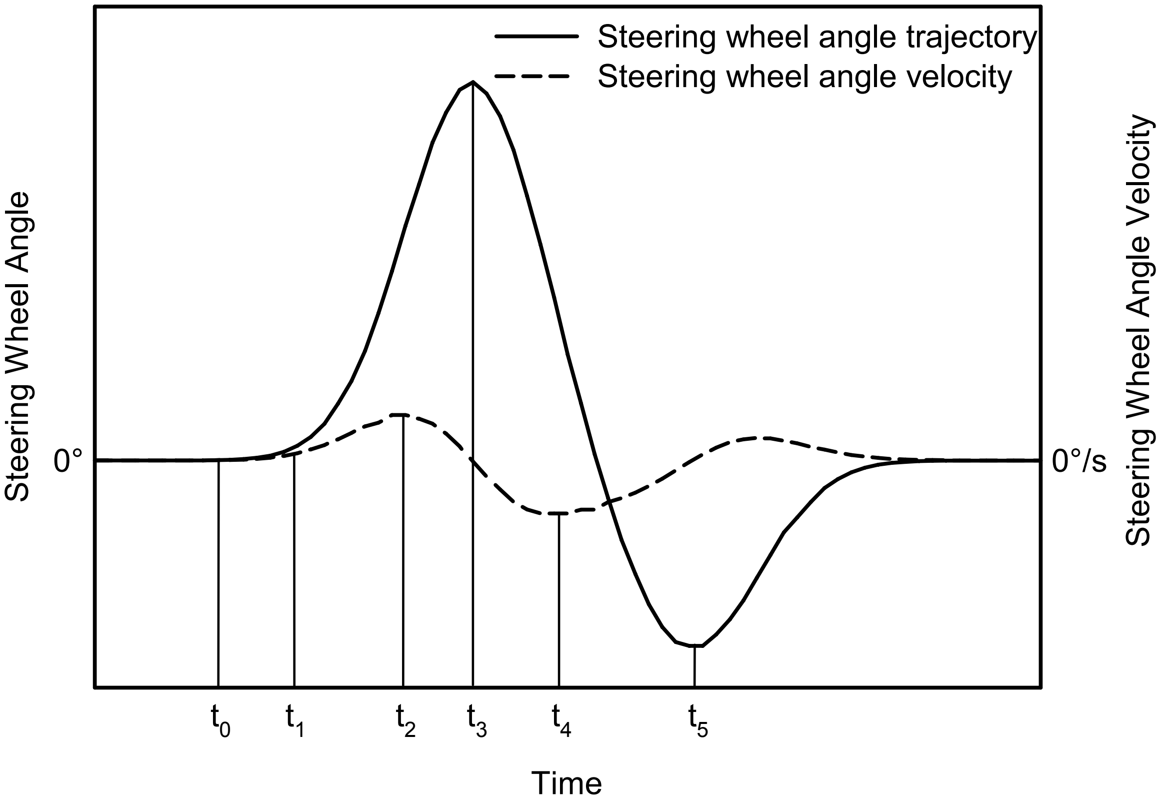

Figure 8: Schematic fragmentation of an idealized steering wheel angle time course during a lane shift. t_0: Onset of the imperative stimulus; t_1: Movement onset; t_2: Peak steering wheel velocity of initial steering wheel submovement; t_3: Peak steering wheel angle at the end of initial steering wheel submovement; t_4: Peak steering wheel velocity of second steering wheel submovement; t_5: Peak (absolute) steering wheel angle at the end of second steering wheel submovement. Four phases can be analyzed: [t_1 ,t_2]: time to peak steering wheel velocity (TTP1); [t_2, t_3]: time after peak steering wheel velocity (TAP1); [t_3, t_4]: time to peak steering wheel velocity (TTP2); [t_4, t_5]: time after peak steering wheel velocity (TAP2).

It could be argued that changes in the kinematic profile might not deliver additional knowledge about movement planning and movement execution processes, since they might vary with corresponding changes in RT. In such a case one might expect high correlations between RT and appropriate kinematic parameters. For example, RT might vary with the peak steering wheel angle in a sense that faster responses might lead to more forceful responses and thus to higher peak steering wheel angles. Alternatively, faster responses might also be linked to faster movements, i.e., to higher PVs. For this reason, in the first experiment RTs were also correlated with the peak steering wheel angle as well as with the peak velocity of the first steering wheel submovement (see Appendix A: Alternative and Additional Calculations). It was found that RT did not vary with PV. However, the analysis of the correlations between RT and the peak steering wheel angle showed a main effect for the precue factor in the lane change direction: the correlation was stronger when the precue information was given than when it was not. Nevertheless, the precue factor for the number of lanes did not influence the correlations, nor did the interaction between both precue factors. One might conclude that RTs and the kinematic patterns are not independent from each other, but the kinematic properties do not only reflect changes in RT. Thus, the kinematic analyses in this thesis seemed to be justified.

Quality checks. Kinematic changes in the steering wheel velocity profile were suspected to go along with qualitative changes of the lane change trajectory. To assess such modifications, two additional measures were introduced to check the lane change quality. First, the number of corrective movements was defined as the number of steering wheel direction changes in the time interval [t_5, t_5 +1s], indicated by the number of zero crossings of the steering wheel angle velocity. Second, the mean lateral position relative to the starting position in the time interval [t_5, t_5 +1s] was analyzed (lateral deviation). This measure can also be understood as the constant error of the lateral position. To better understand the corresponding mean values reported in the empirical result sections, the reader is reminded that a displacement of 20 WTK geometrical units corresponds to the breadth of one lane.

Analysis of variance. All experimental designs in this thesis are within-subject designs with two to four factors. In all experiments the main statistical analysis is a repeated-measures analysis of variance (ANOVA). Probability level for statistical significance in all analyses was $p < 0.05$. When necessary, violations of sphericity were corrected using the Greenhouse-Geisser correction. For each effect, partial eta-squared (η_p^2) was calculated as a measure of effect size.

2.2 Experiment 1: Movement Precuing

In the experiment the movement precuing technique (Requin et al., 1991; Rosenbaum, 1980) is deployed in the lane change task. The general aim of this first approach is to replicate findings from basic research on RT level and to find out the extent to which kinematic properties of the steering wheel movement during a lane change are affected by event-specific response preparation.

2.2.1 Introduction

Driving a car requires a continuous integration of sensory input from the environment and the vehicle in order to prepare upcoming actions. This kind of response preparation can be based on various sources of information such as the curvature of the road, traffic signs, controls and instruments or the front-seat passenger leading the way. With respect to the automotive context, the implementation of advanced driver assistance systems (ADAS) increases. ADAS deliver time-critical information, such as lane departure warnings, lane change assistance, traffic sign recognition or navigational support. These systems aim to better prepare the driver for action (e.g. steering, braking) by providing temporal and/or contextual advance information some time before an action is required. Although many studies investigate the competition of sensory information for attentional resources in driving (e.g. by employing dual-task paradigms, Matthews et al., 1996; Summala et al., 1996) the processes of event-specific response preparation are rather rarely in the focus of interest.

The issue of response preparation has been frequently addressed by basic research (Brunia & van Boxtel, 2000; Müller-Gethmann et al., 2000; Requin et al., 1991). Rosenbaum (1980) provided the movement precuing technique that aimed to assess covert preparatory processes within the motor system. Of interest for the purposes of this first experiment is the robustness and inferential power of the movement precuing paradigm that has been applied to many different areas of research (cf. Müller-Gethmann et al., 2000). It was not only used for the analysis of discrete single-arm aiming movements (Bock & Arnold, 1992; Goodman & Kelso, 1980; Leuthold & Jentzsch, 2001; Rosenbaum, 1980), but also for the analysis of more complex rotating movements (Anson et al., 2000). Long movements can also benefit from preparatory processes (Spijkers & Steyvers, 1984; Vidal et al., 1991).

The aim of this experiment therefore was to investigate response preparation in the lane change task described in the general method section. Lane changing in real driving means smoothly steering from one lane to an adjacent lane. In the current study, precues informed the participants about the direction and/or the number of lanes to be changed in an upcoming lane change maneuver. Since the latter precue can be regarded as the amplitude of the lane change the two most predominant parameters of movement preparation (direction and amplitude) were implemented (according to Bock & Arnold, 1992). Subjects were instructed that even when full advance information was precued, they had to withhold their responses until the fully informative imperative signal appeared and required them to execute the lane change maneuver. Precues and imperative signals were presented in a simulated HUD. With regard to the steering wheel movements during lane changes, movement precuing effects were expected, i.e., reduced RTs depending on the amount of advance preparation. This finding would support the idea of active processes of movement preparation in driving.

As mentioned above, advance information about an upcoming response also affects movement dynamics. To assess whether preparatory effects can also be found for the steering dynamics, steering wheel movements for each lane change were analyzed. Previous studies assumed that response preparation in terms of preprogramming motor parameters changes the kinematic quality of fast movements (van Donkelaar & Franks, 1991a, 1991b). Within the context of the movement precuing paradigm, Mieschke et al. (2001) examined the kinematics of simple aiming movements. The authors found higher peak velocities and shorter times to peak velocity when full advance information was given than when no prior information was available. These findings were explained by a two-component model of limb-control (Beggs & Howarth, 1970; Carlton, 1981; Chua & Elliott, 1993, 1997) which assumes that only the first part of a movement, the ballistic (open-loop) part, can be prepared whereas the second and final part of the movement is under visual closed-loop control. To date it is unclear whether these findings can be generalized to more complex movements such as reciprocal movement sequences in a steering response. For reciprocal movement sequences, the first turning point seems to be particularly relevant, as this movement part is expected to consume an essential amount of movement planning efforts (van Donkelaar & Franks, 1991a). Hence the effects of movement preparation are not necessarily limited to the first ballistic phase of the initial movement. Second, according to Adam et al. (2000), reciprocal movements exhibit a certain mutual interdependence that might become manifest in kinematic parameters as well. In a reciprocal two-element reversal movement, the implementation of the second movement might partially overlap with the execution of the first movement. This is due to the neuromuscular activity during these two movements. The first movement consists of an agonistic and an antagonistic movement phase. First the limb is agonistically accelerated towards the target, and then it is antagonistically decelerated to hit the target precisely. At the same time, this deceleration phase is supposed to serve as agonistic activity for the accelerative phase of the reversal movement, which itself also consists of an accelerative and a decelerative phase bringing the limb back into its start position. Thus, it can be assumed that both movements in a two-element reversal movement are tightly linked and optimally integrated (movement integration-hypothesis, Adam et al., 2000). A change in the velocity profile of the first movement in a two-element reversal movement is therefore likely to be reflected in the velocity profile of the subsequent second movement. In addition to the reciprocal character of the entire lane change steering wheel movement, both effector sides are always tightly linked, as well in space as in time. This tight bimanual coupling is due to the hands' point-symmetric positions on the steering wheel during movement execution. Thus, it can be assumed that the movements of both hands are governed by the same sequence of GMPs or even by one large GMP (Schmidt et al., 1998). Moreover, the bimanual symmetry of the steering movement suggests that both hands produce similar force pulses to move the wheel. This bimanual force production in symmetrical movements is assumed to be governed by the same motor program, whose parameters can be preprogrammed (Rinkenauer, Ulrich, & Wing, 2001).

Based on these considerations, it was expected that the kinematic effects of response preparation could mainly be detected in the velocity profiles of the lane change steering wheel submovements. Steering to maintain the lane mainly relies on visual perceptual input (Hildreth et al., 2000), at least in driving simulations. Although in lane change maneuvers the role of visual feedback is still under discussion (Macuga et al., 2007; Wallis et al., 2002), the steering wheel movement sequence of a lane change can be assumed to be executed in a mixture of open-loop- and visually controlled closed-loop-processes (Godthelp, 1985; Wallis et al., 2007). According to the movement integration-hypothesis (Adam et al., 2000) response preparation advantages achieved for the first submovement should also be reflected in the second reversal submovement. Specifically, symmetrical changes in the velocity profiles were expected especially around the first turning point (van Donkelaar & Franks, 1991a) of the steering response, provided that the amount of advance information is of importance for the ongoing movement as well as for movement onset.

2.2.2 Method

Participants. Twelve participants (age range 19 to 28 years, mean age = 23.25 years, *SD* = 2.60 years) took part in the experiment. All participants were right-handed and had normal or corrected-to-normal vision. Stereo vision and colour vision were found to be normal in all participants. The mean driving experience was 5.33 years (*SD* = 2.54 years) and the yearly driving distance was on average 8,792 km/year (*SD* = 5,306 km/year). Two participants suffered from cyber sickness during the driving task so that all analyses are based on the remaining 10 complete data records.

Driving task, apparatus and stimuli. The apparatus and the driving task corresponded to the general description at the beginning of the empirical section.

The red precues conveyed full information, partial information or no information about the upcoming lane change. No advance information about the demanded movement was communicated by a red horizontal line (7.69° × 0.43° of visual angle, see Figure 9). Precue information about direction was communicated by an arrowhead (2.69° × 2.65° of visual angle), added to the left or right end of the horizontal line. Precue information about the number of lanes to be changed was delivered by one or two vertical lines (0.43° × 2.79° of visual angle) intersecting the horizontal line in the middle. The final imperative stimulus, presented in green and containing all necessary information for the lane change, consisted of a horizontal line, an arrowhead and the respective number of vertical lines.

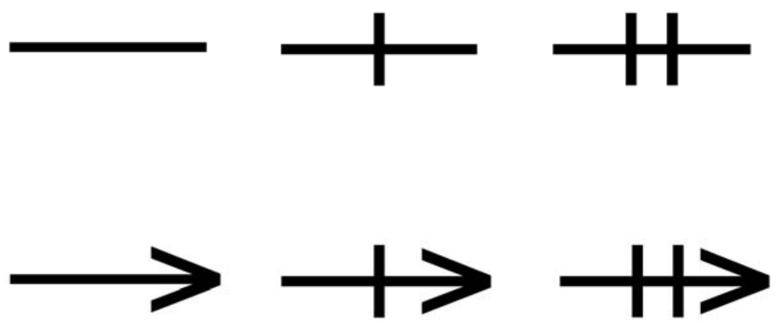

Figure 9: Precues used in Experiment 1 indicating direction and number of lanes of a lane change. First row from left to right: no advance information, lane change by one lane, lane change by two lanes. Second row from left to right: lane change to the right, lane change to the right by one lane, lane change to the right by two lanes.

Procedure. After the general introduction, fulfillment of questionnaires and vision tests the experimental task was explained and participants were familiarized with the steering wheel and the driving task. In a first block of maximally 48 trials participants learned how to interpret the precue stimuli and how to respond to the imperative stimuli while driving with reduced speed. Participants were instructed to generally keep their virtual vehicle in the middle of the lane. They were to react as fast and as accurate as possible to the imperative stimulus with a lane change in the required direction by the indicated number of lanes. The first block was cancelled by the investigator when it was apparently clear that the participant had understood the task and was familiar with the steering wheel. After that a second entire training block of 48 lane change trials at experimental driving speed was conducted. These two training blocks were discarded from data analysis.

The following single driving session consisted of 16 blocks and lasted about 2 hours. Within each block of 48 trials each experimental condition was presented three times in random order. After each block, participants received feedback concerning their mean reaction times and the percental change of the actual mean RT compared with the one of the preceding block. Participants could determine the length of the break between blocks autonomously by starting the next block of trials via the PC keyboard.

Each trial started with an interval of 800 + X ms in which X represents a random variable that follows an exponential distribution with a mean of 1 s (Figure 10). At the end of the interval the precue stimulus was displayed for 300 ms. After precue offset a fixed interval of

1,200 ms followed before the imperative stimulus was presented for 300 ms. A final interval of 2,500 ms was added to let the participant execute the lane change.

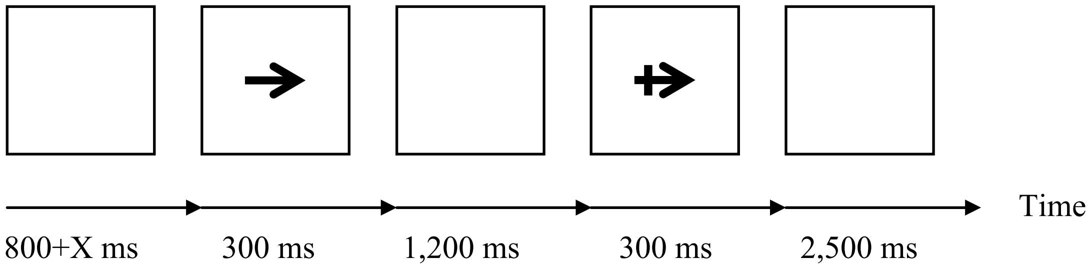

Figure 10: Time course of a single trial in Experiment 1 with exemplary schematic precue and imperative stimulus for a lane change to the right by one lane. The quadratic frame represents the HUD area and was not visible to the participants. Following the variable presentation of a blank screen the precue provided advance information about the lane change direction (the arrow pointing to the right) for 300 ms. After a constant foreperiod of 1200 ms the imperative stimulus provided full information about the direction and the number of lanes (one vertical bar intersecting the horizontal arrow base) of the lane change. Participants were told to react as fast as possible on the onset of the imperative stimulus and had 2500 ms to execute the lane change.

Experimental design. The experimental design was a complete 2×2×2×2 within-subjects design combining four factors. The first factor consisted of the lane change direction (left vs. right); the second consisted of the number of lanes to be changed (one vs. two). The third factor determined if the lane change direction (direction precue) was given or not (with vs. without precue). Finally, the fourth factor was made up of information about the number of lanes (number of lanes precue) to be changed in the upcoming lane change (with vs. without precue). The main dependent variables will be explained in the next section.

Data reduction and data analysis. The steering wheel angle signal was processed as described in the general method section in order to derive RT and kinematic data.

Mean RTs and the quality variables were submitted to a four-way repeated-measures analysis of variance (ANOVA) with direction (left, right), number of lanes (one, two), direction precue (with, without) and number of lanes precue (with, without) as within-participant factors. With respect to the kinematic movement properties, each dependent variable was analyzed in each submovement (initial and second steering submovement) separately. As there were no hypotheses about possible direction effects, each dependent variable was first submitted to an analogous preliminary univariate four-way repeated measures ANOVA. As will be explained in the next section, there were only a few main effects of direction and one interaction involving direction. Thus, all subsequent analyses were collapsed across direction.

2.2.3 Results

Error rates. The overall percentage of erroneous trials was 6.24%. Specifically, anticipations and misses occurred in 4.68% and 0.31% of all trials, respectively. In 1.25% of all trials the participants changed fewer or more lanes than required. Direction errors were not committed.

Reaction times. As expected, the analysis revealed main effects for the factors direction precue ($F(1,9) = 143.76$, $p < 0.01$, $\eta_p^2 = 0.94$) and number of lanes precue ($F(1,9) = 36.36$, $p < 0.01$, $\eta_p^2 = 0.80$). Participants responded faster with advance knowledge about the lane change direction (*M* = 295 ms, *SD* = 54 ms) than without it (*M* = 369 ms, *SD* = 55 ms). The same was true for advance knowledge about the number of lanes (*M* = 317 ms, *SD* = 49 ms vs. *M* = 350 ms, *SD* = 58 ms). In addition a main effect for the number of lanes of the lane change occurred ($F(1,9) = 5.49$, $p < 0.05$, $\eta_p^2 = 0.38$) indicating that mean RTs were slower for two-lane (*M* = 337 ms, *SD* = 57 ms) than for lane changes by one lane (*M* = 331 ms, *SD* = 50 ms).

A significant two-way-interaction between the two precue factors was observed ($F(1,9) = 12.05$, $p < 0.01$, $\eta_p^2 = 0.57$), corroborating the hypothesis that participants produce especially short RTs when both information are given in advance. This finding was confirmed by a two-tailed paired t-test ($t(9) = 3.42$, $p < 0.01$) on the differences of lane changes with and without number of lanes precue. The t-test showed that this difference was much larger when the direction precue was given (*M* = 48 ms, *SD* = 25 ms) than when the respective difference was without direction precue (*M* = 23 ms, *SD* = 17 ms).

However, the two-way interaction was attenuated by a three-way interaction (see Figure 11) between the two precue factors and the factor number of lanes ($F(1,9) = 7.51$, $p < 0.05$, $\eta_p^2 = 0.45$). A two-way repeated measures ANOVA with the two precue factors in the single lane condition revealed the interaction ($F(1,9) = 17.47$, $p < 0.01$, $\eta_p^2 = 0.66$) between the two precue factors. By contrast, the corresponding interaction failed to reach significance in the two lanes condition ($F(1,9) = 4.28$, $p < 0.1$, $\eta_p^2 = 0.32$). Thus, the advantage of full advance information was larger for single-lane changes than for two-lane changes.

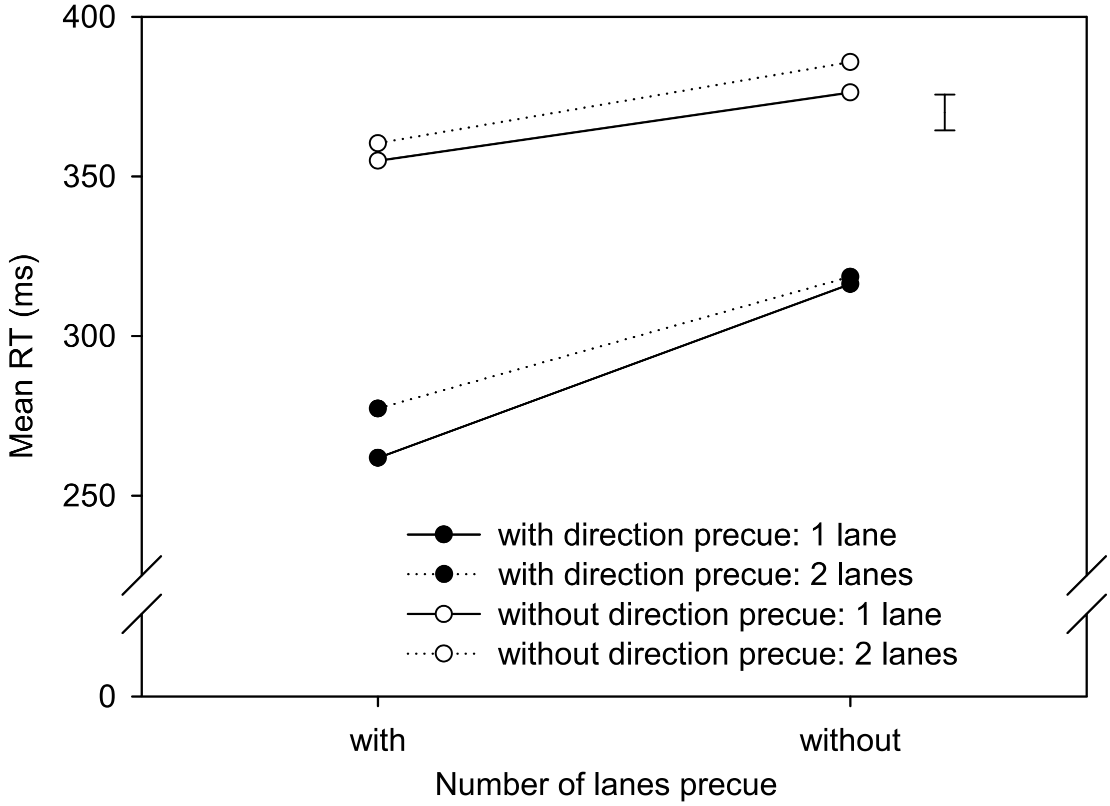

Figure 11: Results of Experiment 1, movement precuing. Mean reaction time (RT) as a function of number of lanes, direction precue availability and lane precue availability. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

Kinematic variables. As described before (see Figure 8), the kinematic variables TTP and TAP were analyzed for the initial and for the second steering wheel submovement. Quality checks of the lane changes were conducted by analyzing the number of corrective movements after the end of the second steering submovement (t_5) for a duration of one second (t_5 + 1s) as well as for the mean lateral deviation of the vehicle in the same interval. As there was no deeper interest in the effects of the factor direction, all data were collapsed across this factor. All results in this section and in the following sections are based on three-way repeated measures ANOVA with the factors number of lanes (one, two), direction precue (with, without) and number of lanes precue (with, without) as well as within-participant factors. The respective dependent variable is stated at the beginning of each paragraph. All mean values and standard deviations are illustrated in Table 2. Before discussing the statistical results, the observed steering wheel angle trajectories will be described shortly.

Steering wheel angle trajectory. As presented in Figure 12, the observed lane change steering wheel angle trajectory resembled those typically obtained in lane change experiments (Salvucci & Liu, 2002; van Winsum et al., 1999). It first exhibited a sharp increase of the steering wheel angle to its first peak, whereas the second peak was shallower. Such a shape asymmetry corresponds to the considerations of Salvucci and Gray (2004), who assume a lane change to require an update of the visual near and far points in order to control the maneuver. The newly chosen near point first exerts a large influence on the steering behaviour. Then, as the vehicle moves closer to this actual near point, its influence decreases, which in turn leads to the second peak with a smaller amplitude.

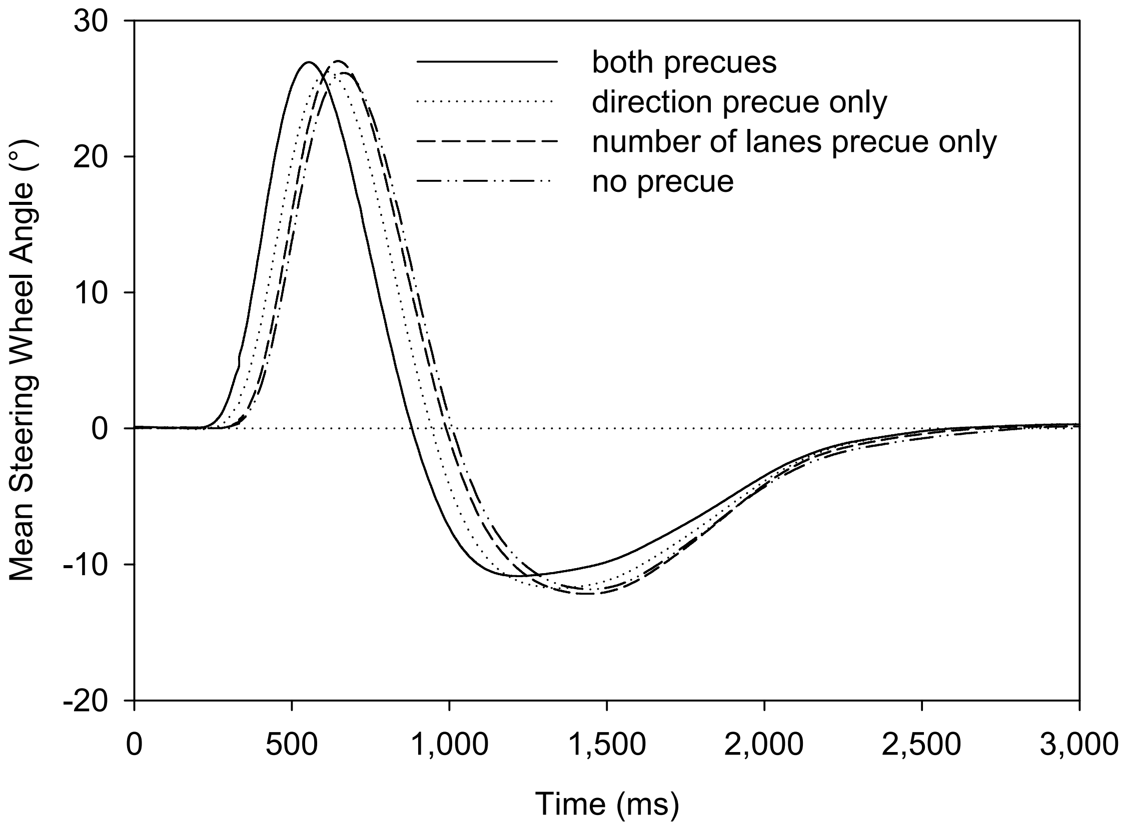

Figure 12: Results of Experiment 1 for the steering wheel angle trajectory. Mean steering wheel angle (collapsed across lane change direction and number of lanes) as a function of direction precue availability and number of lanes precue availability. Onset of the imperative stimulus at Time = 0 ms.

Steering wheel velocity. Figure 13 illustrates the first deviation of the steering wheel angle, i.e., the steering wheel velocity. As was described schematically in Figure 8, the maxima, zero crossings and minima of this function were used in order to derive the durations of the kinematic phases of the first and the second lane steering submovement. Although the third submovement was not statistically analyzed it seems to be clear from visual inspection of Figure 12 and Figure 13 that the full advance information condition (both precues) shows the earliest and smoothest return to a stable steering wheel position.

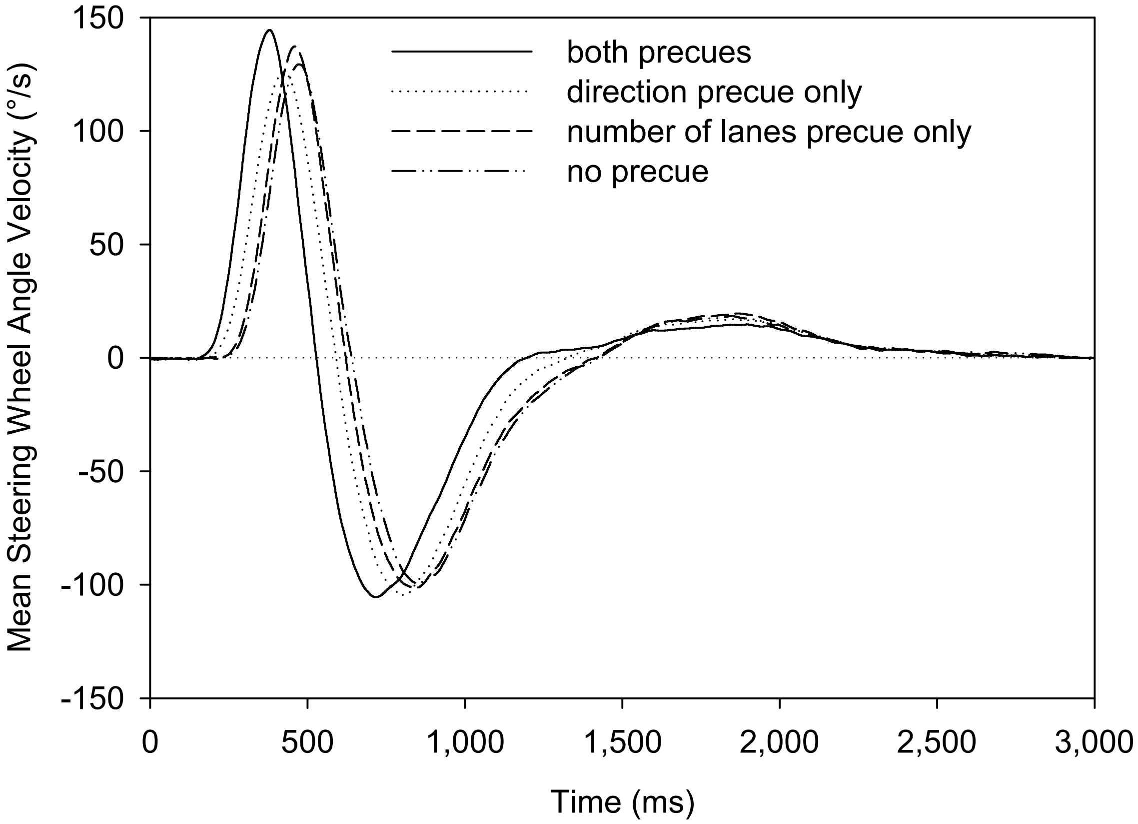

Figure 13: Results of Experiment 1 for the steering wheel angle velocity profile. Mean steering wheel angle velocity (collapsed across lane change direction and number of lanes) as a function of direction precue availability and number of lanes precue availability. Onset of the imperative stimulus at Time = 0 ms.

Initial steering wheel submovement

Time to peak steering wheel velocity (TTP1). As one could expect TTP1 was shorter ($F(1,9) = 25.92$, $p < 0.01$, $\eta_p^2 = 0.74$) for changes by one ($M = 139$ ms, $SD = 16$ ms) than by two lanes ($M = 150$ ms, $SD = 21$ ms). More important, the number of lanes precue yielded shorter TTP1s ($F(1,9) = 6.63$, $p < 0.05$, $\eta_p^2 = 0.42$) when advance information was given ($M = 143$ ms, $SD = 18$ ms) than when it was not ($M = 147$ ms, $SD = 19$ ms). The interaction between both precue factors marginally missed the trend to significance ($F(1,9) = 3.19$, $p = 0.1$, $\eta_p^2 = 0.26$).

Time after peak steering wheel velocity (TAP1). A main effect was observed for the factor number of lanes ($F(1,9) = 97.16$, $p < 0.01$, $\eta_p^2 = 0.92$), viz. TAP1 was shorter for single (*M* = 126 ms, *SD* = 25 ms) than for two-lane-changes (*M* = 174 ms, *SD* = 36 ms). Of course, this effect is due to the longer distance that has to be traveled when crossing two lanes instead of one. More interestingly, the direction precue ($F(1,9) = 41.35$, $p < 0.01$, $\eta_p^2 = 0.82$) and the number of lanes precue ($F(1,9) = 25.25$, $p < 0.01$, $\eta_p^2 = 0.74$) yielded main effects for TAP1. TAP1 was shorter when the lane change direction was known (*M* = 146 ms, *SD* = 29 ms) than when it was not (*M* = 154 ms, *SD* = 40 ms). In analogous fashion, the number of lanes precue led to shorter TAP1s when it was given (*M* = 147 ms, *SD* = 29 ms) than when participants did not know the number of lanes in advance (*M* = 153 ms, *SD* = 31 ms).

A two-way interaction was observed for the factorial combination of number of lanes and number of lanes precue ($F(1,9) = 7.92$, $p < 0.05$, $\eta_p^2 = 0.47$). In order to throw more light on this interaction the data was collapsed across the factor direction precue. A two-tailed paired t-test ($t(9) = 2.83$, $p < 0.05$) on the differences of trials with and without number of lanes precue in single and two-lane-changes showed that the number of lanes precue led only to a shortening of TAP1 of lane changes by two lanes (*M* = 10 ms, *SD* = 7 ms) but not by one lane (*M* = 1 ms, *SD* = 4 ms). Another two-way interaction was revealed for both precue factors ($F(1,9) = 19.42$, $p < 0.01$, $\eta_p^2 = 0.68$). After averaging the data across the number of lanes factor, three Bonferroni-corrected two-tailed paired t-tests revealed that complete advance information particularly shortened the duration of TAP1 (*M* = 142 ms, *SD* = 27 ms) compared with a mere direction precue (*M* = 151 ms, *SD* = 31 ms), a mere number of lanes precue (*M* = 154 ms, *SD* = 31 ms) or no advance information at all (*M* = 155 ms, *SD* = 32 ms).

Second steering wheel submovement

Time to peak steering wheel velocity (TTP2). First, as expected, TTP2 was dependent on the number of lanes ($F(1,9) = 187.69$, $p < 0.01$, $\eta_p^2 = 0.95$). Changes by two lanes led to longer TTP2s (*M* = 503 ms, *SD* = 122 ms) than changes by one lane (*M* = 347 ms, *SD* = 98 ms). Second, TTP2 was shorter ($F(1,9) = 12.94$, $p < 0.01$, $\eta_p^2 = 0.59$) when advance information about direction was given (*M* = 418 ms, *SD* = 108 ms) than when not (*M* = 432 ms, *SD* = 111 ms). A third main effect was observed for the number of lanes precue factor ($F(1,9) = 6.08$, $p < 0.05$, $\eta_p^2 = 0.40$) indicating a shorter TTP2 when advance information about the number of lanes was given (*M* = 421 ms, *SD* = 110 ms) than when not (*M* = 428 ms, *SD* = 109 ms). A two-way interaction emerged between the factors direction precue and number of lanes precue ($F(1,9) = 31.73$, $p < 0.01$, $\eta_p^2 = 0.74$). Data was then collapsed across the factor number of lanes in order to investigate the reason for this interaction in more detail. Three Bonferroni-corrected two-tailed paired t-tests revealed that TTP2 was particularly short (*M* = 412 ms, *SD* = 110 ms) when both information about direction and number of lanes were known in advance. TTP2 summed up to *M* = 425 ms (*SD* = 108 ms, $t(9) = -3.49$, $p < 0.01$) when only direction was precued. When only the number of lanes precue was given, TTP2 totaled *M* = 433 ms (*SD* = 111 ms, $t(9) = -3.92$, $p < 0.01$). Without any advance information, TTP2 aggregated to *M* = 431 ms (*SD* = 112 ms, $t(9) = -3.30$, $p < 0.01$).

Time after peak steering wheel velocity (TAP2). The experimental factors had no effects on TAP2. The interaction between the factors number of lanes and direction precue was not significant ($F(1,9) = 4.01$, $p = 0.08$).

Table 2: Overview of kinematic results in Experiment 1. Means (*M*) of kinematic variables and their standard deviations (*SD*) as a function of number of lanes, direction precue and number of lanes precue for the initial steering phase and for the second steering phase. TTP: time to peak steering wheel velocity; TAP: time after peak steering wheel velocity. The indices 1 and 2 indicate the initial steering wheel submovement and the second steering wheel submovement.

Direction Precue:	with				without			
Number of lanes Precue:	with		without		with		without	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				1 lane				
Initial steering wheel submovement								
TTP1 (ms)	137	18	144	18	136	14	140	18
TAP1 (ms)	119	24	124	25	132	25	130	26
Second steering wheel submovement								
TTP2 (ms)	333	97	341	98	357	98	355	102
TAP2 (ms)	450	188	444	145	454	130	455	125
				2 lanes				
Initial steering wheel submovement								
TTP1 (ms)	149	21	153	22	149	22	150	21
TAP1 (ms)	163	33	179	40	176	37	180	37
Second steering wheel submovement								
TTP2 (ms)	487	125	509	120	508	125	508	122
TAP2 (ms)	478	136	460	126	459	100	448	107

Quality checks

Corrective movements. The ANOVA revealed a main effect for the factor number of lanes ($F(1,9) = 41.53$, $p < 0.01$, $\eta_p^2 = 0.82$). Lane keeping was corrected more often after a lane change by one ($M = 6.69$, $SD = 1.74$) than by two lanes ($M = 4.93$, $SD = 1.11$).

Lateral deviation. The constant error was dependent on the factors number of lanes ($F(1,9) = 526.91$, $p < 0.01$, $\eta_p^2 = 0.98$) and direction precue ($F(1,9) = 6.62$, $p < 0.05$, $\eta_p^2 = 0.37$). Trivially, the participants were further away from their starting position in two-lane changes ($M = 35.09$, $SD = 2.52$) than in single-lane changes ($M = 17.18$, $SD = 1.63$). In trials with advance information about the lane change direction the mean lateral position was closer to the middle of the target lane ($M = 26.46$, $SD = 1.60$) than in trials without advance information ($M = 25.81$, $SD = 1.93$). The main effects were moderated by a two-way interaction of both factors ($F(1,9) = 21.78$, $p < 0.01$, $\eta_p^2 = 0.72$). A two-tailed paired t-test

($t(9) = 4.63$, $p < 0.01$) on the differences of trials with and without direction precue for lane changes by one and by two lanes revealed that the advantage of the precue information led to a closer mean lateral position to the target lane ($M = 1.28$, $SD = 0.77$) only in two-lane changes, but not in single-lane changes ($M = -0.01$, $SD = 0.99$).

2.2.4 Discussion

The aim of this experiment was to investigate event-specific response preparation in a driving context. Therefore, the lane change task was employed because the maneuver required by this task corresponds to a standard traffic situation and has been used in many previous studies (Salvucci & Liu, 2002; van Winsum et al., 1999). In this experiment participants were informed partially or fully about the upcoming maneuver in order to make inferences about response preparation processes. It was hypothesized that precuing effects analogous to basic research could be revealed in a continuous driving task that requires both-handed steering actions. It was assumed that reductions of RT with increases of advance information can be attributed to covert response preparation processes. In addition, a kinematic analysis was conducted for a more detailed understanding of movement processes affected by preparatory processes. The discussion is structured analogously to the results section.

Reaction times. Compared with trials with no advance information, RT was significantly shortened when either advance information about direction or number of lanes of the upcoming lane change was provided. The RT advantage was much larger for information about direction than about the number of lanes. In addition, when both factors were known in advance, RT was especially short for single lane changes whereas this specific advantage could not be confirmed for two-lane changes. Beyond these effects, RT was significantly prolongated in two-lane compared with single lane changes.

In general, this result represents the typical pattern of results, i.e., the precuing effect, obtained in former movement precuing studies (RT advantages for each precue factor, and shortest RTs for full advance information) (e.g. Anson et al., 2000; Leuthold et al., 1996; Spijkers & Steyvers, 1984). As each precue yielded RT advantages by itself, it can be assumed that the parameters can be specified without fixed order (Anson et al., 2000). The greatest RT benefit was derived from advance direction information. Since advance information about the number of lanes can be interpreted analogously to the movement amplitude, these results are consistent with previous work: Anson et al. (2000) found that the benefit of mere directional advance information was larger than that of exclusive advance information about movement extent. The prolongation of RTs in lane changes by two lanes seems to reflect evidence from basic findings as well. Since a lane change by two lanes requires a longer movement time than a lane change by one lane, it can be expected that programming time for this movement is longer. This “short-long” or “dit-dah” effect has been observed for simple as well as for complex movements (Klapp, Wyatt, & Lingo, 1974; Spijkers & Steyvers, 1984). However, this effect might also be an artifact resulting from the choice of a relative RT criterion, since the mean RT difference between lane changes by one and lane changes by two lanes was not significant in the RT calculations based on an absolute criterion (see Appendix A: Alternative and Additional Calculations).

In the lane change task, participants perform bimanual steering movements. In this movement sequence, three almost reciprocal submovements are coordinated with both hands. As most studies in the area of movement preparation have focused on movements executed with one single arm or hand instead of both limbs, the RT results of this experiment were not clear a priori. However, this was not the only difference between the current task and those used in basic research. Aside from the bimanual nature of the task, participants were continuously required to keep their virtual vehicle in the middle of the lane. This aspect, which demanded continuous control and monitoring between and during the experimental trials, distinguishes the task from related response preparation studies in which participants only perform discrete reactions on imperative stimuli without performing a task between trials. Despite these differences, the pattern of results was quite similar to that obtained in discrete reaction studies. Thus, the results suggest that steering movements in lane changes may benefit from analogous preparatory processes as for example unimanual aiming movements. Moreover, one might speculate that the process of motor preparation is not seriously degraded by the additional deployment of attentional resources that were used to fulfill the constant vigilance task of lane keeping.

Of course, in a movement precuing paradigm the number of reaction alternatives is reduced when precue information is given. Complete advance information changes a choice reaction task to a simple reaction task. Thus, RT advantages obtained by advance information do not necessarily reflect response preparation processes but could also be due to central response selection processes (Goodman & Kelso, 1980). One argument against this interpretation is the difference in size between the observed main effects of the precue factors although both reduced the number of reaction alternatives equally. This argumentation is corroborated by the interaction between the precue factors, which suggests that RT precuing advantages are not simply caused by a reduction of the number of response alternatives. However, this interaction was only found for lane changes by one lane. Nevertheless, since there was a trend to a two-way interaction also for lane changes by two lanes it seems probable that the significance level might have been reached with more experimental power. Finally, one might also argue that the pattern of effects is a result of the chosen RT limits defining anticipation errors. For this reason, the effects of anticipation errors were also evaluated by analyzing the data without lower RT boundary as well as with a lower limit of 200 ms for anticipatory errors. Of course, the elimination of the lower limit strengthens the influence of anticipations, whereas the boundary of 200 ms reduces their respective effects. Since the pattern of results remained stable in both cases, the RT limits are not believed to explain the results.

Kinematic variables. An additional kinematic analysis was conducted in order to investigate the possible impact of response preparation on response execution for upcoming lane changes. To this end, the movement integration-hypothesis positing a tight neuromuscular integration of reversal movements from research about reciprocal aiming movements (Adam et al., 2000) was adopted. Since the first turning point of a reversal movement seems to require most of the planning efforts, benefits of event-specific response preparation were expected to be revealed around the first peak steering wheel angle. Such a benefit might be revealed by shorter kinematic phases centered around this peak.

With regard to the influence of the experimental factors on movement kinematics, data analysis revealed a variety of differential effects. Most important, the temporal kinematic pattern of the entire steering wheel movement was influenced by the amount of advance information. The precue information about direction and/or the number of lanes primarily modified the duration of the two kinematic phases around the first peak steering wheel angle. TAP1 was shortened by any precue information and was shortest when the upcoming lane change was fully specified. Analogous modifications were observed for TTP2. This pattern of results argues for a functional dependence between the first and the second steering submovement, as predicted by the movement integration-hypothesis (Adam et al., 2000). The tight integration of the submovements, in time as well as in space, might have favoured the close relationship between the kinematic phases around the first peak steering wheel angle. In accordance with experimental results concerning reciprocal flexion/extension movements (van Donkelaar & Franks, 1991a) the effects centered around the first peak steering wheel angle. Van Donkelaar and Franks observed increases in premotor time when a point of reversal was introduced into a movement. Premotor time is determined by the time between stimulus onset and the appearance of the muscle action potential (Botwinick & Thompson, 1966). The increase in premotor time might indicate larger planning efforts associated with reversal than with unidirectional movements. Within the current experiment, the amount of advance information before the movement was varied, not the movement pattern itself. A possible reason for the shortening of the kinematic phases around the turning point may stem from reduced on-line preparation efforts during the controlled phase of the initial steering wheel submovement (TAP1). Since response preparation was supported by advance information, preprocessing of the required motor activity seemed to be possible to a large extent. TAP1 may also have profited from these preprocessing efforts. Due to the interdependence between reciprocal movements, this optimization could then lead to an analogous shortening of the ballistic phase of the second steering submovement (TTP2). Clearly, it has to be stated that the time to reach peak steering wheel velocity in the second steering phase cannot be considered as an exclusively ballistic phase. Phase duration was consistently longer than 300 ms, a time in which visual feedback can easily intervene into movement execution (Carlton, 1981). As it was not possible to establish a reliable kinematic phase following the second peak steering wheel angle, the only indication that the third submovement was executed predominantly under visual on-line control was the absence of experimental effects during the controlled phase before the second peak (TAP2).

Moreover, advance information about the number of lanes shortened the ballistic phase of the initial steering submovement (TTP1) when lane changes by two lanes were required. With regard to simple aiming movements, Mieschke et al. (2001) found higher peak velocities and shorter times to peak velocity when full advance information was given than when no prior information was available. Hence, this finding only partly confirms the two-component model of limb-control (Beggs & Howarth, 1970; Carlton, 1981; Chua & Elliott, 1993, 1997). This model assumes that only the first part of a movement, the ballistic (open-loop) part, can be prepared in advance, whereas the second and final part of the movement is under visual closed-loop control. However, the generalization from a simple unidirectional aiming movement to a complex steering movement may be limited for several reasons. First, the controlled phase of the initial steering submovement (TAP1) was also shortened, suggesting a benefit of response preparation in this phase. Second, the length of both the ballistic and the controlled phase of the initial steering submovement (TTP1 and TAP1) were comparably short, almost symmetrical. A symmetrical velocity profile of a short movement seems to reflect a smooth movement prepared in advance by the CNS (Flash & Hogan, 1985). However, Mieschke et al. (2001) found asymmetrical velocity profiles in their task. The third aspect that distinguishes the current finding from that of Mieschke et al. is that it only appeared in one specific case, but was not elicited for example by the direction precue or full advance information. The effects in these latter two cases were generally larger than the effect of the number of lanes precue. Consequently, they should have also contributed to shortening the first ballistic phase (TTP1) if this had been the only movement phase prepared in advance. Thus, it might be assumed that both-handed point-symmetrical movements, especially steering, dispose of proper kinematic qualities that cannot be inferred directly from aiming movements. Further research integrating evidence about symmetrical and asymmetrical both-handed movements, for example from the field of GMP research (Schmidt et al., 1998), is necessary.

Furthermore, one can argue that if response preparation leads to shorter RTs and shorter kinematic phase durations, then the quality of the lane changes might suffer. It might be possible that a RT reduction and a shortening of phase durations do not reflect response preparation processes but rather are a consequence of less optimally executed maneuvers, possibly due to time pressure or hectic movements. To account for this possibility, the number of corrective movements after the end of the second steering phase and the mean lateral position during this period were examined. With regard to the factors carrying advance information, it was observed that two-lane changes were more optimally executed when direction information was available. In these cases, the vehicle was closer to the target lane than without it. There were no more effects of advance information on these variables. Of course, the lateral displacement in single-lane changes after the end of the second steering submovement was smaller than in two-lane changes. Also, the number of corrective movements was larger in single-lane changes than in double-lane changes. Consequently, the quality of the lane changes was not reduced but rather improved by advance information. Therefore, the facilitations in RT and MT cannot be attributed to a speed-accuracy tradeoff.

Conclusion. With regard to the analysis of RT, response preparation can be regarded as a relevant principle. Response preparation also plays a role in driving, at least in the lane change task considered in this experiment. RT benefits were found depending on the amount of advance information and the pattern of results was comparable with the findings in basic research studies. There was also evidence for the impact of response preparation processes on the motor performance of the steering movement, since the phase durations around the first peak steering wheel angle (TAP1 and TTP2) were shortened with an increasing amount of advance information. The kinematic effects in these phases mirrored the RT effects. Since the quality of the lane changes did not suffer from reduced phase durations, the kinematic effects may be explained by way of the increased efficiency of movement execution predicted by the movement integration-hypothesis (Adam et al., 2000). Presumably, response preparation does not only shorten the information processing chain; it also has beneficial effects on the deployment of motor resources.

2.3 Experiment 2: Temporal Preparation

As described in the introductory sections, the processes of temporal preparation (Niemi & Näätänen, 1981) constitute the second abundant research area besides the processes of event-specific preparation. Therefore, the second experiment served to test the effects of temporal preparation in the newly developed lane change task. As in the first experiment, the intention was to replicate RT findings from basic research literature. In addition, this section will assess the effects of temporal preparation on the kinematic properties of the steering wheel movement.

2.3.1 Introduction

In driving, temporal preparation is a self-evident feature that is often ignored. The most typical example of a simple reaction task involving temporal preparation consists in a driver approaching a green traffic light that suddenly turns yellow. This switch indicates that the red stop signal will follow in a few moments. This allows the driver to slow down in advance instead of being surprised by a sudden stop signal. Of course, temporal preparation is not only elicited by explicit traffic signals. Drivers anticipate the behaviour of other road users and time their own reactions to the current traffic requirements. Thus, temporal preparation can be understood as a permanent ongoing process in driving. However, it is unclear to what extent temporal preparation in driving can be supported by temporal precues, since the driving task is different from basic laboratory settings. The latter tasks are mostly static in nature, whereas driving always requires monitoring and control of a dynamic scenario.

Insofar as the author is aware, the effects of pure temporal preparation in driving have not been assessed in detail. In a series of three experiments Nickerson, Collins and Markowitz (1969) examined the effects of uncertain warning signals on RT. In the experiment, subjects had to push the brake pedal as soon as possible after the presentation of a danger light. Nickerson et al. varied the FP length between warning and danger signal and the probability of occurrence of both signals. In general it was found that a warning signal could be an effective means of decreasing RT in operational traffic situations, even if the warning signal was not fully predictive of the danger signal. The authors argued that both the probability of the danger signal following the warning signal and the time interval between both signals should be investigated in applied situations in order to learn about specific types of response preparation. The timing of warning signals has also been investigated in the area of rear-end collision systems. These experiements observed fewer collisions and reduced collision severity for early than for late or no warnings at all (J. D. Lee, McGehee, Brown, & Reyes, 2002).

As was pointed out in the general introduction, temporal preparation by precue leads to a better timing of response readines because uncertainty about when the imperative stimulus will appear is reduced (Niemi & Näätänen, 1981). The experimental approach to measure temporal preparation is based on RT as a dependent variable, i.e., good temporal preparation is assumed to reveal itself by shorter RTs compared with experimental conditions where temporal preparation is not facilitated. As to the locus of this RT effect in a steering task, one might assume that temporal preparation at a motor level is more valuable than at a perceptual level for releasing the motor response at the appropriate moment, especially since the task does not require high perceptual performance (Correa et al., 2006).

When temporal preparation is studied, the distribution of FPs, i.e., the time interval between the offset of a warning stimulus and the onset of an imperative stimulus, is crucial for the expectancy of results. The differences between a blocked and a variable FP paradigm were explained in the introduction. In blocked FP paradigms, RTs increase progressively with FP length (Niemi & Näätänen, 1981), since time uncertainty increases when the FP is prolonged. In variable FP paradigms, RTs are usually shortest after the longest FP and longest after the shortest FP (Näätänen, 1970) since the subject's time uncertainty is reduced as the time after the warning signal elapses (Näätänen, 1970). Finally, in non-aging FP paradigms, a U-shaped RT function might be expected. In this experiment, a non-aging FP paradigm was approximated by a systematic distribution of discrete FPs (Niemi & Näätänen, 1981), i.e., the FP durations were systematically doubled from the shortest to the longest FP.

Although temporal preparation is assumed to affect the implementation of motor commands (Tandonnet, Burle, Vidal, & Hasbroucq, 2003), it remains unclear to what extent it also affects the movement kinematics of the executed response. According to the "motor-readiness model" (Näätänen, 1971), response force is assumed (and also was found) to overshoot the required motor threshold when temporal expectancy of the imperative stimulus is low, thus resulting in more forceful responses than when expectancy is high (Mattes & Ulrich, 1997; Mattes, Ulrich, & Miller, 1997; van der Lubbe et al., 2004). These studies have shown that RT and response force can be considered complementary inferential tools with regard to human information processing. As far as the author is aware, only several studies have analyzed the relation between FP duration and MT. Frowein and Sanders (1978) followed the suggestion of Fitts (1954) that RT and MT can be considered as largely independent processes, a hypothesis that was also supported by the absence of any effects of FP duration on movement velocity in another study (Meulenbroek & van Galen, 1988).

Regarding the current lane change task, a fundamental effect of temporal preparation was expected in the second experiment. Based on this effect, lane changes should occur sooner when temporal precues are present than when they are not. As it was tried to approximate non-aging FPs, a U-shaped RT function was expected, i.e., RT was assumed to be shortest with a medium FP duration and longer with the shortest and the longest FP durations. With regard to the kinematic analysis, one might assume that low expectancy of the imperative stimulus, especially in the case of no temporal preparation, might lead to an overshoot in response force, causing a higher maximal steering wheel velocity in the initial steering wheel movement. With regard to the length of TTP and TAP for each respective steering phase, this experiment remained exploratory in nature.

2.3.2 Method

Participants. Eight female and four male subjects (mean age M = 21.75 years, SD = 2.53 years, range 19 to 29 years) took part in the experiment. Five participants had corrected-to-normal vision; the others reported normal vision. Mean yearly driving experience summed up to 7,908 km/year (SD = 9,732 km/year). Colour vision and stereoscopic vision were found to be normal in all participants. Ten participants were right-handed and two left-handed, by self-report.

Driving task, apparatus and stimuli. The apparatus and the driving task corresponded to the general description at the beginning of the empirical section. In each trial, the participants received a temporal precue which was followed by an imperative stimulus after a variable FP. The red precue stimulus was an asterisk with a diameter of 2.33°. It conveyed no information about the upcoming lane change. The imperative stimulus, a green arrow with a shaft size of 4.30° × 0.39° and a head size of 2.51° at the arrow base and 0.39° at the arrowhead, delivered the information about the required lane change direction.

Procedure. After an introduction given by the investigator and the fulfillment of all tests and questionnaires, the participants learned in a first block of no more than 45 trials how to interpret the temporal precue and the imperative stimuli while driving with reduced speed. Participants were instructed to keep their virtual vehicle in the middle of the lane. They were to react as fast as possible to the imperative stimulus with a lane change in the indicated direction. The first block was cancelled by the investigator when it was apparently clear that the participant had understood the task and was able to manipulate the steering wheel. Then an entire training block of 45 lane change trials at experimental driving speed was conducted. The first and second training blocks were discarded from data analysis.

The following single driving session lasted about two hours. It consisted of 16 blocks. Within each block of 45 trials, each experimental condition was presented four times in random order. Each block contained five catch trials (one per FP) requiring the participants to drive straight ahead. After each block, participants received feedback concerning their actual mean RT. They were informed as well about the percental change of the actual mean RT compared with the mean RT of the preceding block. Participants determined the length of the break between blocks autonomously by starting the next block of trials via the PC keyboard.

Each trial started with an interval of 800 + X ms in which X was a random variable that followed an exponential distribution with a mean of 1 s (Figure 14). At the end of the interval, the precue stimulus was displayed for 300 ms. After precue offset, a FP of 300, 600, 1,200 or 2,400 ms was implemented before the imperative stimulus was presented for 300 ms. In a fifth condition (“no FP”), no precue was presented at all. A final interval of 3,500 ms was added to let the participant change the lane.

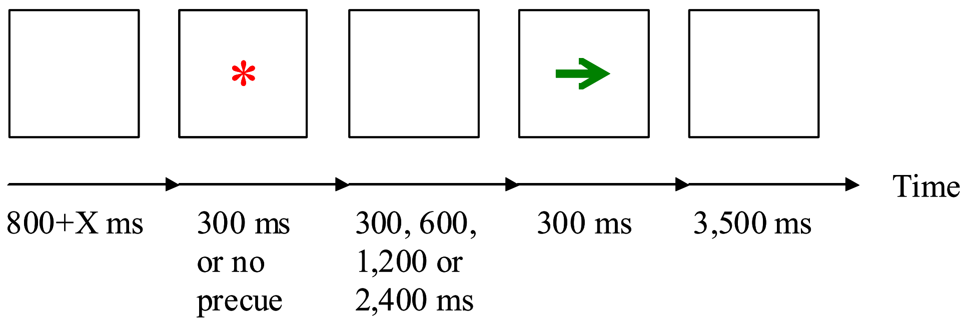

Figure 14: Time course of a single trial. The quadratic frame represents the HUD area and was not visible to the participants. Following the variable presentation of a blank screen, either the precue appeared for 300 ms providing only temporal advance information or no precue was given. After a variable FP of 300, 600, 1,200 or 2,400 ms, the imperative stimulus provided the direction of the lane change. Participants were told to react as quickly as possible on the onset of the imperative stimulus and had 3,500 ms to execute the lane change.

Experimental design. The experimental design was a complete 2×5 within-subjects design. The first factor consisted of the lane change direction (left vs. right) and the second of the FP (no FP, 300, 600, 1,200, 2,400 ms). The dependent variables comprised RT, error rate, the duration of the four kinematic phases TTP1, TAP1, TTP2 and TAP2 and the two qualitative variables, i.e., the number of corrective steering movements and the mean lateral deviation.

Data reduction and data analysis. Data reduction and analysis were performed as described at the beginning of the empirical section. Mean RTs of all trials with correct responses were submitted to a two-way repeated-measures analysis of variance (ANOVA) with direction (left, right) and FP (no FP, 300, 600, 1,200, 2,400 ms) as within-participant factors. Analogous ANOVAs were performed for the durations of the four kinematic phases TTP1, TAP1, TTP2 and TAP2 as well as for the number of corrective steering movements and the mean lateral deviation. Since an additional explicit hypothesis was formulated for PV during the initial steering wheel submovement, the effects of the experimental factors on PV were analyzed, too.

2.3.3 Results

As was pointed out in section 1.2.2, the manipulation of FPs typically neglects the duration of the warning stimulus during which temporal preparation might already start (Los & Schut, 2008). Since this problem is relevant for the discussion of results in this experiment as well as in Experiment 3, 4 and 7, all FPs will also be expressed as SOAs in all respective figures. However, since it is the author’s impression that in the field of temporal preparation the term FP is mainly used to describe the period of temporal preparation, this term is typically used in the discussions of the respective experiments.

Error rates. The overall error rate was 3.13% for all trials. In 1.28% of all trials, participants changed more than one lane. In 0.91% of all trials, participants steered in the wrong direction; 0.62% were misses and 0.27% were anticipations. 0.05% of all trials were eliminated because participants obviously left the lane without reacting to any signal, possibly due to drowsiness. The error rates did not vary with the experimental factors.

Reaction times. The lane change direction did not affect RT ($F(1,11) = 2.37$, $p = 0.15$, see Figure 15). As expected, a main effect of FP was observed ($F(1.71,18.76) = 102.02$,

$p < 0.01$, $\eta_p^2 = 0.90$). Pairwise comparisons with Bonferroni-correction for multiple testing demonstrated that RTs in trials without temporal precue were longer (M = 440 ms, SD = 38 ms) than in trials with temporal precues, regardless of FP (FP 300 ms: M = 368 ms, SD = 23 ms, $p < 0.01$; FP 600 ms: M = 369 ms, SD = 27 ms, $p < 0.01$; FP 1,200 ms: M = 373 ms, SD = 27 ms, $p < 0.01$; FP 2,400 ms: M = 382 ms, SD = 28 ms, $p < 0.01$). In addition, the RTs in the FPs 300 ms ($p < 0.05$), 600 ms ($p < 0.01$) and 1,200 ms ($p < 0.01$) were shorter than in the longest FP of 2,400 ms. The ANOVA also revealed an interaction between direction and FP ($F(2.81,279.97) = 3.14$, $p < 0.05$, $\eta_p^2 = 0.22$).

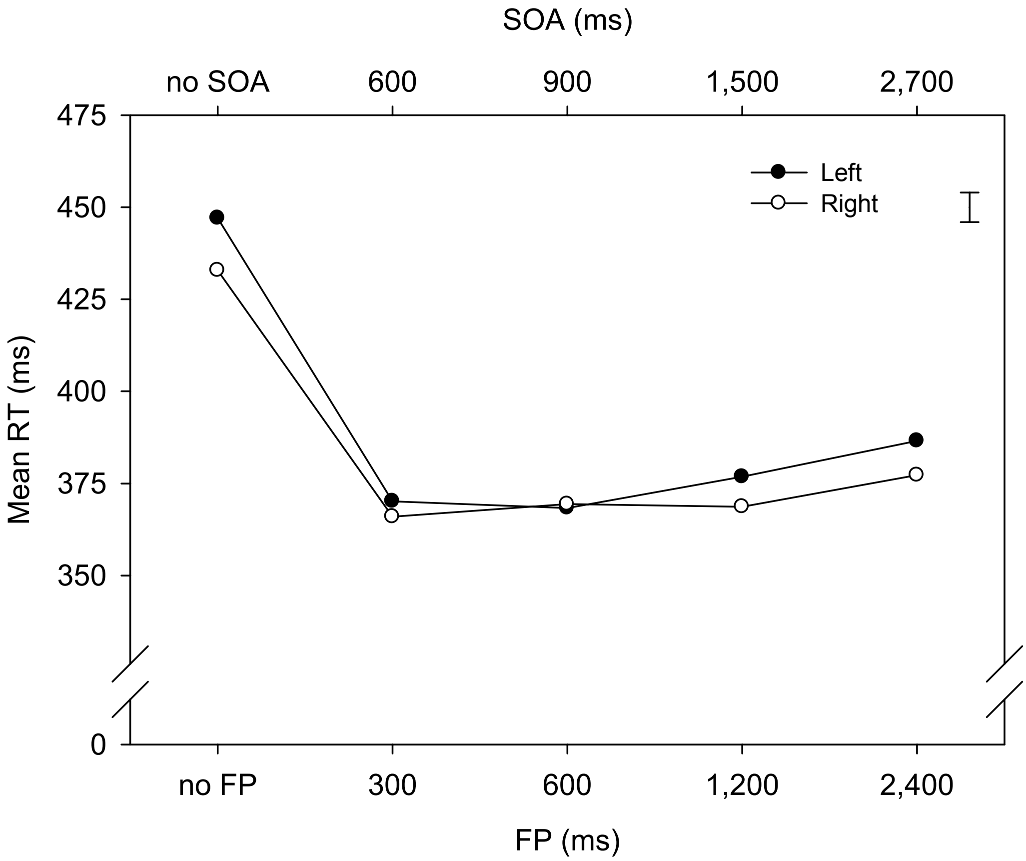

Figure 15: Results of Experiment 2 for temporal preparation. Mean reaction time (RT, in milliseconds) as a function of FP/SOA and lane change direction. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

Kinematic variables. As in the preceding experiment, the statistical kinematic analysis is preceded by a descriptive presentation of the steering wheel angle trajectory and its corresponding velocity profile.

Steering wheel angle trajectory. The steering wheel angle trajectory is illustrated in Figure 16. The visual inspection confirms the statistical results indicating the RT disadvantage for trials without temporal precue. Apart from this observation, the different FPs do not seem to have markedly influenced the trajectory.

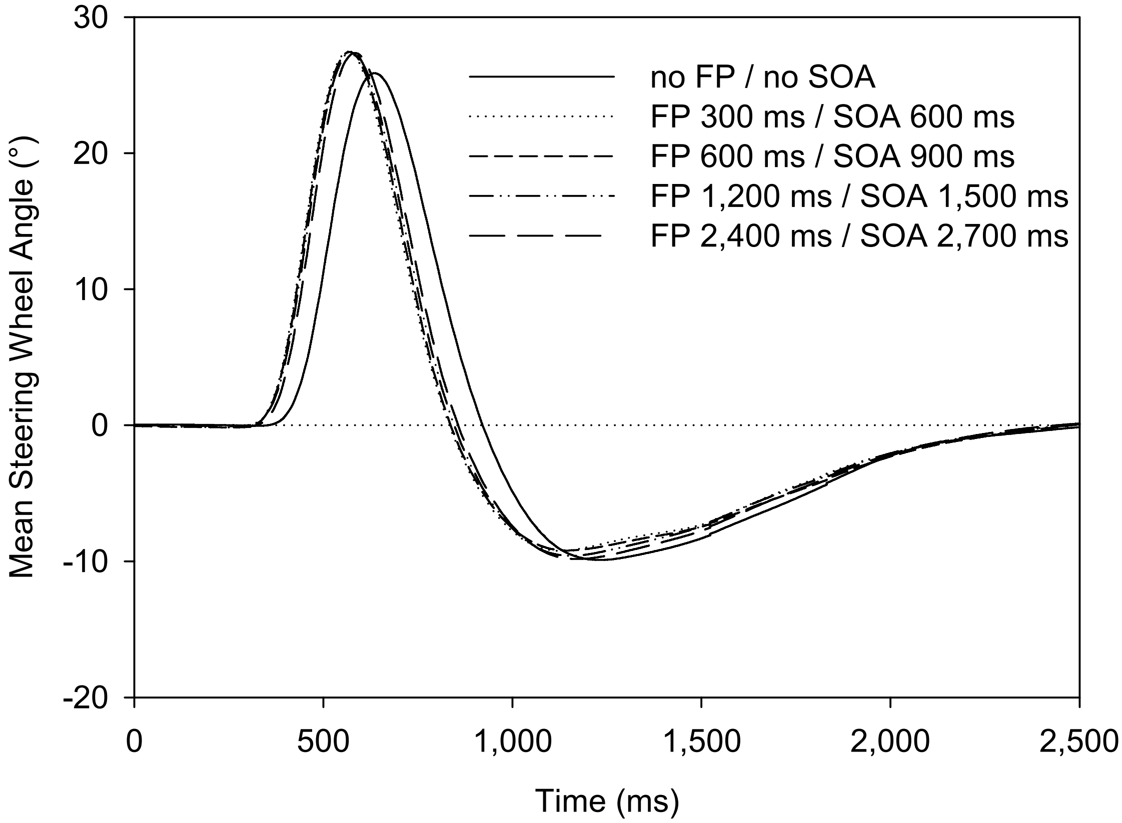

Figure 16: Results of Experiment 2 for the steering wheel angle trajectory. Mean steering wheel angle (collapsed across lane change direction) as a function of FP/SOA. Onset of the imperative stimulus at Time = 0 ms.

Steering wheel velocity. A visual comparison between the steering wheel velocity profile of this experiment (see Figure 17) and that of the preceding experiment (see Figure 13) reveals two things. On the one hand, the current profile is more compressed in time. On the other hand, the first two peaks of the current velocity profile are markedly higher (in absolute values). The main reason for this change in profile can be found in the fact that the preceding experiment also required lane changes by two lanes. Obviously, these maneuvers require longer movement times than lane changes by one lane. As a result, the steering wheel movements in Experiment 2 were executed faster and the velocity profile returned to the baseline sooner.

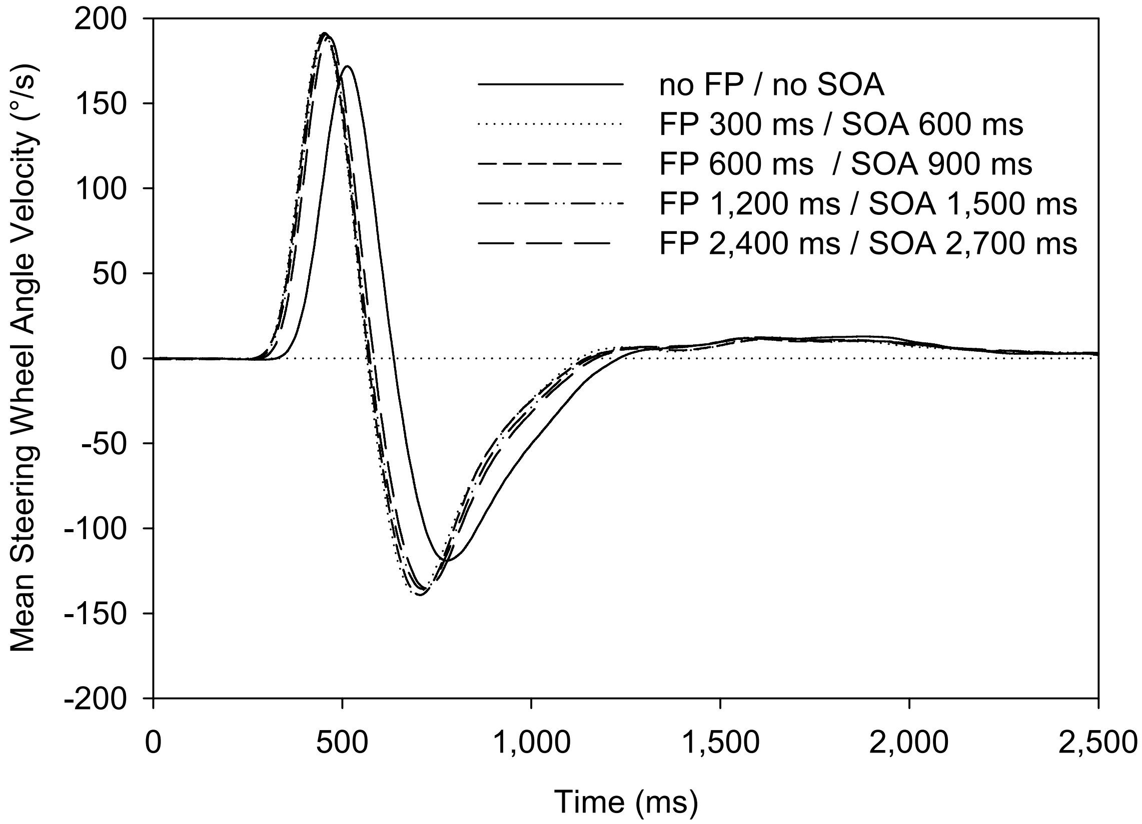

Figure 17: Results of Experiment 2 for the steering wheel angle velocity profile. Mean steering wheel angle velocity (collapsed across lane change direction) as a function of FP/SOA. Onset of the imperative stimulus at Time = 0 ms.

Initial steering wheel submovement

Peak steering wheel velocity (PV). FP did not influence PV. However, the factor direction affected PV significantly ($F(1,11) = 10.82$, $p < 0.01$, $\eta_p^2 = 0.50$). PV was higher in lane changes to the left (*M* = 261°/s, *SD* = 145°/s) than in those to the right (*M* = 250°/s, *SD* = 135°/s).

Time to peak steering wheel velocity (TTP1). TTP1 was not affected by FP duration. The factor direction led to a main effect ($F(1,11) = 5.49$, $p < 0.05$, $\eta_p^2 = 0.33$), indicating shorter TTPs for lane changes to the left (*M* = 129 ms, *SD* = 35 ms) than to the right (*M* = 135 ms, *SD* = 39 ms). No interaction was detected.

Time after peak steering wheel velocity (TAP1). TAP1 was not influenced by any experimental factor.

Second steering wheel submovement

Time to peak steering wheel velocity (TTP2). The factor direction did not exert any influence on TTP2. However, TTP2 was affected by FP duration ($F(4,44) = 4.37$, $p < 0.01$, $\eta_p^2 = 0.28$). Pairwise comparisons with Bonferroni-correction for multiple testing documented that TTPs in the 300 ms FP (*M* = 325 ms, *SD* = 137 ms) and the 600 ms FP (*M* = 329 ms, *SD* = 137 ms) were shorter than in the longest FP of 2,400 ms (*M* = 336 ms, *SD* = 141 ms).

Time after peak steering wheel velocity (TAP2). TAP2 was not affected by any experimental factor.

Quality checks

Corrective movements. The number of corrective movements was affected by the lane change direction ($F(1,11) = 9.48$, $p < 0.05$, $\eta_p^2 = 0.46$). Lane changes to the right were corrected more often (*M* = 6.27, *SD* = 1.62) than lane changes to the left (*M* = 5.80, *SD* = 1.31). FP duration did not influence this variable.

Lateral deviation. A main effect of FP duration was observed for the mean lateral deviation ($F(4,44) = 4.12$, $p < 0.01$, $\eta_p^2 = 0.27$). Post-hoc Bonferroni-corrected pairwise comparisons showed that the mean lateral position of the simulated vehicle tended to be closer to the starting position (i.e., farther away from the middle position in the target lane) in the 300 ms FP condition (*M* = 19.91, *SD* = 1.65) than in the 600 ms FP condition (*M* = 20.37, *SD* = 1.55, $p < 0.1$) or in the 2,400 ms FP condition (*M* = 20.50, *SD* = 1.56, $p < 0.1$). The factor direction influenced the mean lateral deviation ($F(1,11) = 5.19$, $p < 0.05$, $\eta_p^2 = 0.32$) insofar as lane changes to the left were closer to the target lane (*M* = 20.77, *SD* = 2.04) than those to the right (*M* = 19.75, *SD* = 1.22).

2.3.4 Discussion

As expected, the experiment confirmed that temporal preparation in an applied lane change task improves behavioural performance. Contrary to the initial assumption, the kinematic properties, especially PV, were largely independent of temporal preparation.

Reaction times. Mean RTs were shorter when a temporal warning signal was available than when no temporal warning signal was given. The RT benefit is possibly due to the reduction of uncertainty about when the imperative stimulus will occur (Niemi & Näätänen, 1981). The mean RTs only partly followed a U-shaped function and were hence inconsistent with the initial assumption. Mean RTs were already minimal after the shortest FP of only 300 ms and did not decrease when FPs of a medium duration were presented. This is contrary to findings indicating non-minimal RTs in the shortest FP condition (Näätänen, 1970) when variable FPs are used. Only in the longest FP condition (2,400 ms) mean RTs were longer, as expected. Several reasons might explain these observations.

The choice of FPs might not have favoured the observation of an initial decrease of RTs to a minimum at a medium FP. As the shortest FP was 300 ms long and the warning signal was displayed for an additional 300 ms, the participants had an effective period (SOA respectively) of 600 ms for temporal preparation (with regard to the effective time course of preparation cf. Los & Schut, 2008). This duration is sufficient for building up a state of readiness (Bertelson & Tisseyre, 1968). Thus, only the introduction of shorter FPs and shorter precue durations that in sum cover potentially critical FP durations of less than effective 300 ms would probably reveal the expected course of RTs. An additional factor influencing the pattern of results could have been the no FP condition. In this condition, no precue was presented and, as expected, mean RTs were longest compared with all other conditions. Although this condition successfully showed a general advantage of temporal preparation it could have modified the general course of time uncertainty in a variable FP paradigm. Since the participants had to expect to react without any precue, even the shortest FP might have facilitated the preparation of an optimal state of readiness. A comparable result was found in the first experiment of Nickerson et al. (1969), who also made use of a no FP condition. In Nickerson's experiment, RTs were shortest in the two shortest FP conditions (125 ms and 250 ms), but in this case the result was attributed to a very short movement time. In the current experiment, an alternative explanation for the minimal RTs in the shortest FP can be found in the task characteristics of a lane change. The driving task requires permanent attention by the driver, as he or she is continuously required to keep the vehicle in the middle of the lane, even between two different trials. One could argue that permanent attention to the driving task also favoured fast reactions in the shortest FP condition.

RTs showed no differences over a FP range of 900 ms (FP 300 ms to FP 1,200 ms). Such a flat course of RTs over such a large range of FPs is not consistent with the literature, especially when non-aging FPs are deployed. Usually, temporal preparation helps to built up a state of readiness that is of short duration (Alegria, 1974) and cannot be extended to a length of approximately 1 s. This is due to the fact that maintaining a high degree of response readiness is exhausting, so that the peak of response readiness can possibly be maintained only for a short duration between 0.1 and 0.4 s (Alegria, 1974; Gottsdanker, 1975; Näätänen, 1970). So if a preparation period of effectively 600 ms (SOA 600 ms, FP 300 ms respectively) was sufficient to reach an optimal state then any longer FP should have yielded poorer results. Again, one can assume that the characteristics of the lane change task were responsible for this untypical result. Permanent attention to keeping the lane may hide the RT differences that are typically found between different FPs in a range of approximately 1 s. Thus, the driving task may be the reason that the effects of different FPs cannot be distinguished as precisely as in discrete and static tasks.

As observed here, RTs increased with the longest FP of 2,400 ms and perhaps would continue increasing with even longer FPs. The typical effect of non-aging FPs was approximated. As this assumption cannot be clarified here, only experimental variations of the FP design (e.g., by making use of longer FPs and by deploying FPs of different relative frequencies or continuous FPs) could shed more light on this issue. Also, temporal preparation might be further facilitated when expectancy within a block of trials is not changed (Correa et al., 2006). A blocked FP paradigm might better discriminate temporal preparation effects between different FPs than a variable FP paradigm.

Kinematic variables. The kinematic analysis did not confirm the initial assumption of an overshooting PV in the initial steering wheel submovement. Although low expectancy of the imperative stimulus in the no FP condition was reflected by prolonged RTs, the PV of the initial steering wheel submovement was not affected by FP duration. The exploratory analysis of the kinematic movement phases did not deliver a consistent picture of systematic FP effects. In the two shortest FP conditions, only TTP2 was shortened in comparison with the longest one. This effect can hardly be explained by the available evidence from the literature. A tentative conclusion from this result would confirm the assumption that temporal preparation turns out to be mostly independent from the movement execution of a lane change. This interpretation is in line with previous results (Fitts, 1954; Frowein & Sanders, 1978; Meulenbroek & van Galen, 1988). This explanation is also supported by the missing correspondence between RT and kinematic effects, which points to a dissociation between temporally prepared information processing and final movement execution. Although there was no main effect of direction on RT, TTP1 was shortened for lane changes to the left. Moreover, lane changes to the left revealed fewer corrective steering movements than lane changes to the right. Since the majority of the participants were right-handed one might assume that the initially upper position of the right hand in a lane change to the left induces a more efficient control of the entire steering wheel movement compared with its initially lower position in lane changes to the right. Since effects of direction were not in the focus of this study, this kind of effects potentially based on handedness or usual side of driving remains speculative (see e.g. Wallis et al., 2002). Another inconsistency between RT and MT measures is revealed by the mean lateral deviation. Although the longest FP condition led to longer RTs than the preceding three shorter FPs, the shortest FP disclosed the lowest mean lateral deviation from the starting position after the end of the second steering wheel submovement. In other words, in the shortest FP condition the participants were unable to position the vehicle as near to the target lane as in the longer FPs (except the 1,200 ms FP), although RT was already minimal and even shorter than in the longest FP. Such a result pattern – an inverse relation between reaction speed and accuracy – suggests a potential speed-accuracy-tradeoff (SAT, Rinkenauer, Osman, Ulrich, Müller-Gehtmann, & Mattes, 2004). Typically, SAT effects are believed to affect premotor and motor processes of RT (Rinkenauer et al., 2004). However, in this case, the SAT seems to be carried over to the response execution, since it was indicated by a poorer quality of the vehicle position after the steering wheel movement. As a consequence and contrary to the initial conclusions of the RT analysis, the shortest FP of 300 ms cannot be regarded as optimal. Although this non-optimality is not reflected by the course of RTs, it seems to be in-line with the assumption of Näätänen (1970), who argued against minimal RTs in the shortest FP condition in a variable FP paradigm. In view of the analysis of the mean lateral deviation, RT results can be relativized.

Conclusion. So far, there appears to be a positive behavioural effect of temporal warning signals on steering RTs in a lane change task. RT was minimal already after an effective FP duration of 600 ms and remained minimal until an effective FP duration of 1,500 ms. Closer analysis of the mean lateral vehicle position revealed a potential SAT-effect for the shortest FP, so that the optimal temporal preparation period lasted from effective 900 ms to effective 1,500 ms. RT increased only with the longest FP (2,400 ms). The kinematic properties were found to be mostly independent of temporal preparation. The prevailing view of independence of RT and kinematic properties in temporal preparation studies was supported by the inconsistent result patterns of RTs, MTs and quality variables in this lane change task.

2.4 Experiment 3: Movement Precuing and Temporal Preparation

Combining the generally independent approaches of temporal and event-specific preparation in one experiment is not very common in basic research. As a result, interactions between the processes are rarely investigated. However, as will be explained in the introduction of this third experiment, both processes seem to be relevant for an applied context such as driving. In Experiment 3, it was asked to what extent both preparatory processes exert a common influence on lane change performance.

2.4.1 Introduction

The third experiment intended to approach the real case of driver advance information by enhancing temporal precues through contextual (event-specific) information. In contrast to pure temporal preparation, the latter form of preparation conveys information about what to do instead of only when to do it. Often the temporal aspect of response preparation is covered by contextual information delivered in a warning signal that allows preparation for a certain response or at least for certain response characteristics. Each traffic sign – denoting for a dangerous curve, a closed lane, an upcoming exit or crossing – does not only deliver information about when an object will appear but also about the relevant response characteristics (the direction of the curve, the required lane change, the distance in which the vehicle must be stopped). With the help of such information, the driver can prepare an adequate reaction (e.g., steering or braking). Of course, ADAS typically incorporate both temporal and contextual aspects, as their function mainly consists in facilitating the driving performance by providing real-time advice, instructions and warnings (Brookhuis et al., 2001). Therefore, in most cases response preparation in driving might represent a combination of temporal and event-specific preparation mechanisms, thus contributing to the difficulty of modelling the highly complex driver behaviour (see e.g. Salvucci, 2006).

With growing experience, driving becomes a highly automated routine, so that many tasks in driving (steering, accelerating, braking, changing gears) become well-learned processes. Certain motor programs are built up with time and will be retrieved and run when necessary. The required motor program can be prepared and deployed more effectivity with contextually relevant advance information than without it. In driving, ADAS and traffic signs usually deliver full advance information about the upcoming tasks (turn right in 100 meters, stop the car at the next crossing etc.). The contextual information might contain explicit information about distance that also serves for the appropriate timing of the required action. For this reason, one can assume that in a real environment event-specific and temporal preparation act in parallel and can each enhance the other.

Most studies investigating temporal preparation found influences on late motor processes, especially when the task was not perceptually demanding (Correa et al., 2006). Although not exclusively, event-specific preparation exerts its influence at a motor level (Leuthold et al., 1996; Müller-Gethmann et al., 2000). As there is a close link between temporal and motor processing (Rosenbaum & Collyer, 1998), it could be assumed that both processes support each other, given a task that requires mainly motor performance and does not emphasize specific perceptual processing. As a lane change task mainly requires the perfectly timed release of a motor response instead of high discrimination efforts, the largest benefit from temporal preparation in this task probably will reveal itself at the motor level. As far as the author is aware, only a few studies have investigated the potential interaction between temporal and event-specific preparation. This might be due to the fact that each mechanism of preparation is difficult to explain for itself (Requin et al., 1991). In one experiment combining both types of preparation, additive effects of both preparation factors suggested independent preparation processes (Spijkers & Steyvers, 1984).

The third experiment in this study aimed at investigating the effects of event-specific and temporal preparation in a lane change task. Contrary to Experiment 1, event-specific preparation was manipulated only in two steps: Advance information about the direction of an upcoming lane change was available or not. Thus, in this first approach to the subject, a partial advance information condition was not realized. Temporal preparation was manipulated as in Experiment 2, except that the no FP condition was discarded.

With regard to RT, the hypotheses in Experiment 3 were as follows. RT advantages for trials in which event-specific preparation was facilitated over trials in which event-specific preparation was not supported were expected. With respect to temporal preparation, the shortest RT was expected to be linked to a medium FP duration. In order to enhance the chances for this finding, the no FP condition (i.e., a condition with no temporal preparation) was dropped. The remaining four FPs were chosen as in Experiment 2 so as to maintain comparability between the experiments. Finally, both preparatory mechanisms were assumed to exert their influence mainly at motor levels, so that an interaction between temporal and event-specific preparation was expected according to the AFM logic (Sternberg, 1969).

With regard to the lane change steering wheel movement's kinematic properties, the preceding experiments have delivered differential results with regard to event-specific and temporal preparation. Event-specific preparation seemed to support response execution to a certain extent, i.e., the kinematic phases around the first peak steering wheel angle were shortened predominantly. On the one hand, this pattern of results was interpreted as evidence for the movement integration-hypothesis (Adam et al., 2000) reflecting the tight linkage between the first two steering wheel submovements in time as well as in space. On the other hand, since the pattern of kinematic results mirrored the pattern of RT results, it was also considered as evidence for preparatory effects helping to optimize the steering reaction in a lane change task. Temporal preparation did not lead to consistent effects on kinematic properties. It rather seemed to increase the noise in the response execution instead of optimizing the movement. Based on these results, the third experiment was expected to replicate these findings. More clearly, it was assumed that temporal preparation would not affect movement execution in a concise manner. Such an observation would further support the notion that, when it comes to temporal preparation, information processing and movement execution are independent (Fitts, 1954; Frowein & Sanders, 1978; Meulenbroek & van Galen, 1988). Of course, such a finding cannot be interpreted as experimental evidence for this assumption, since null effects always include the possibility of type II errors. To the contrary, event-specific preparation was expected to shorten TAP1 and TTP2, thus optimizing the efficiency of movement execution.

2.4.2 Method

Participants. Among 15 participants were six males and nine females with a mean age of 23.47 years (*SD* = 3.74 years, range 19 to 34 years). Six participants had corrected-to-normal vision and nine participants reported normal vision. Twelve participants were right-handed, the remaining three were left-handed, by self-report. Participants had a mean yearly driving experience of 7,933 km/year (SD = 7,304 km/year).

Driving task, apparatus and stimuli. The setup of the fixed-base simulator and the entire experimental setting were as in the preceding experiments. The same imperative stimuli were used as in Experiment 2. Regarding the precue stimuli, an additional precue in form of an arrow pointing to the left or to the right and thus conveying advance information about lane change direction was introduced. This precue corresponded in size exactly to the imperative stimulus used in Experiment 2, but was presented in red colour.

Procedure. Compared with the general course of Experiment 2, modifications were as follows. The first two training blocks consisted of 48 trials each. They were followed by 16 experimental blocks of 48 trials each. Within each block, each experimental condition was presented randomly three times. There were no catch trials. The timing of events corresponded perfectly to Experiment 2, except that there was no condition without temporal precue.

Experimental design. A complete 4×2×2 within-subjects design was used with all participants performing the same number of trials and conditions. The FP duration (300, 600, 1,200, 2,400 ms), the direction of the lane-change (left, right) and the precue information about the lane-change-direction (with vs. without advance information) served as experimental factors. The dependent variables were RT, error rates, the kinematic variables TTP1, TAP1, TTP2 and TAP2 as well as the two qualitative variables.

Data reduction and data analysis. Data processing as well as the definition of RT, errors and kinematic variables corresponded to the general description at the beginning of this empirical section. Error rates were submitted to a three-way repeated measures ANOVA with FP duration (300, 600, 1,200, 2,400 ms), direction precue (with, without) and direction (left, right) as within-participants factors. Analogous ANOVAs were calculated for RT as well as for the kinematic variables and the quality variables.

2.4.3 Results

Error rates. 3.46% of all trials were discarded from data analysis due to errors; 2.08% were anticipations; 0.43% were misses. In 0.88% of all trials participants changed by more than one lane. In 0.07% they steered in the wrong direction. 0.01% of all trials were eliminated due to unexpected maneuvers, possibly due to drowsiness. Only anticipations were influenced by the experimental factors. A main effect of direction precue was observed ($F(1,14) = 37.91$, $p < 0.01$, $\eta_p^2 = 0.73$), illustrating that the participants anticipated the lane change more often in trials with advance direction information than without it.

Reaction times. The ANOVA (see Figure 18) revealed main effects for the factors FP ($F(2.12,29.66) = 6.34$, $p < 0.01$, $\eta_p^2 = 0.31$) and direction precue ($F(1,14) = 232.12$, $p < 0.01$, $\eta_p^2 = 0.94$). Bonferroni-corrected pairwise comparisons revealed that RTs in the FPs 600 ms (M = 341 ms, SD = 47 ms) and 1,200 ms (M = 346 ms, SD = 51 ms) were shorter than in the FP 2,400 ms (M = 356 ms, SD = 55 ms, $p < 0.01$ respectively). RTs in trials with direction precue (M = 313 ms, SD = 50 ms) were shorter than in trials without it (M = 383 ms, SD = 53 ms). The interaction between both factors was significant ($F(3,42) = 2.84$, $p < 0.05$, $\eta_p^2 = 0.17$). As the lane change direction exerted no influence, data was collapsed across this factor. Three Bonferroni-corrected paired samples t-tests on the RT differences between trials with direction precue and trials without it revealed a significant difference between the 300 ms FP and the 2,400 ms FP. In the shortest FP, the RT difference (M = 64 ms, SD = 20 ms) was smaller ($p < 0.017$) than in the longest FP (M = 76 ms, SD = 20 ms).

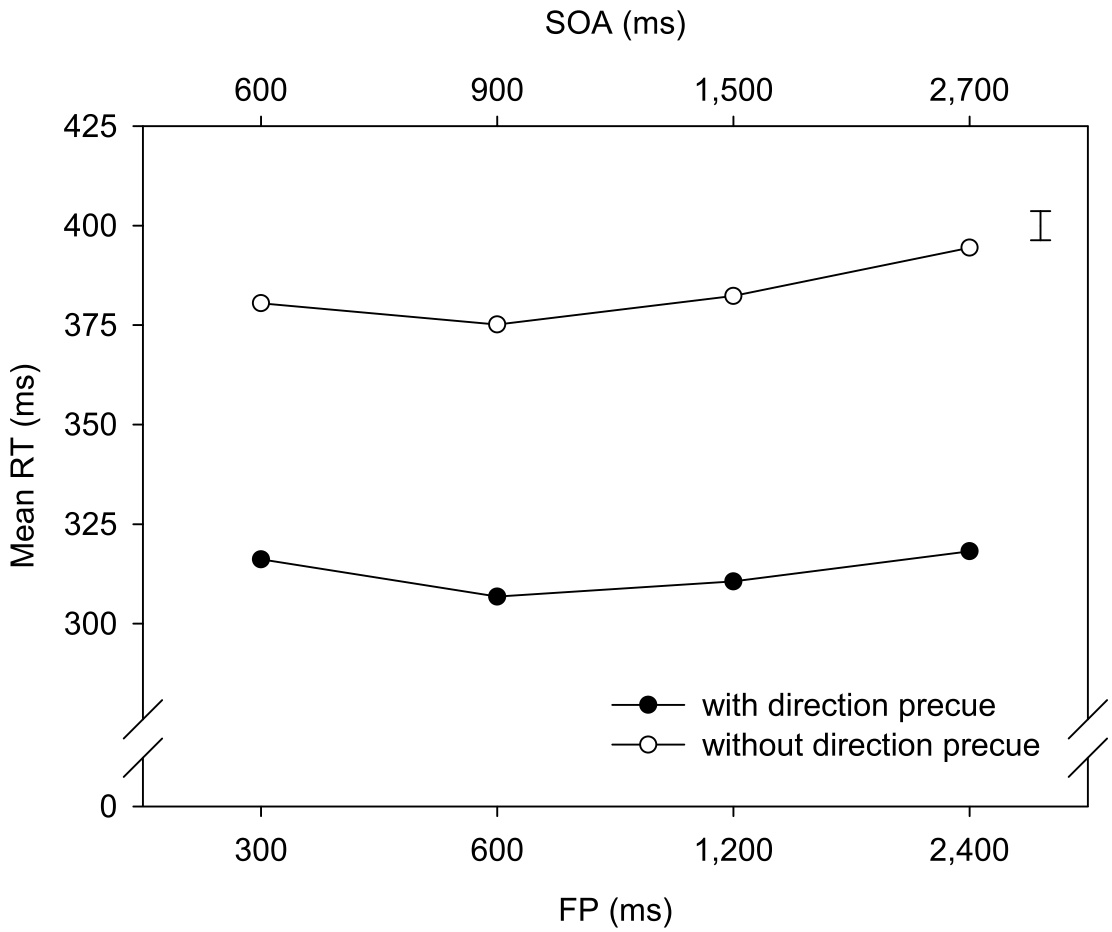

Figure 18: Results of Experiment 3 for temporal and event-specific preparation. Mean reaction time (RT, in milliseconds) as a function of FP/SOA and availability of the direction precue. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002)

Kinematic variables. All mean values and standard deviations of the two kinematic phases are illustrated in Table 3.

Steering wheel angle trajectory. The steering wheel angle trajectory is plotted in Figure 19. Visual inspection of the trajectory reveals an earlier onset of the steering wheel response in trials with directional precue than in trials without it. However, FP duration seems to have an impact on the first peak steering wheel angle, since this angle appears to be lowest for the longest FP duration, especially in the condition with direction precue. The temporal course of the steering wheel profile more closely resembles that of Experiment 2 than that of Experiment 1. This might be due to the fact that the current experiment only required lane changes by one lane, not by two lanes.

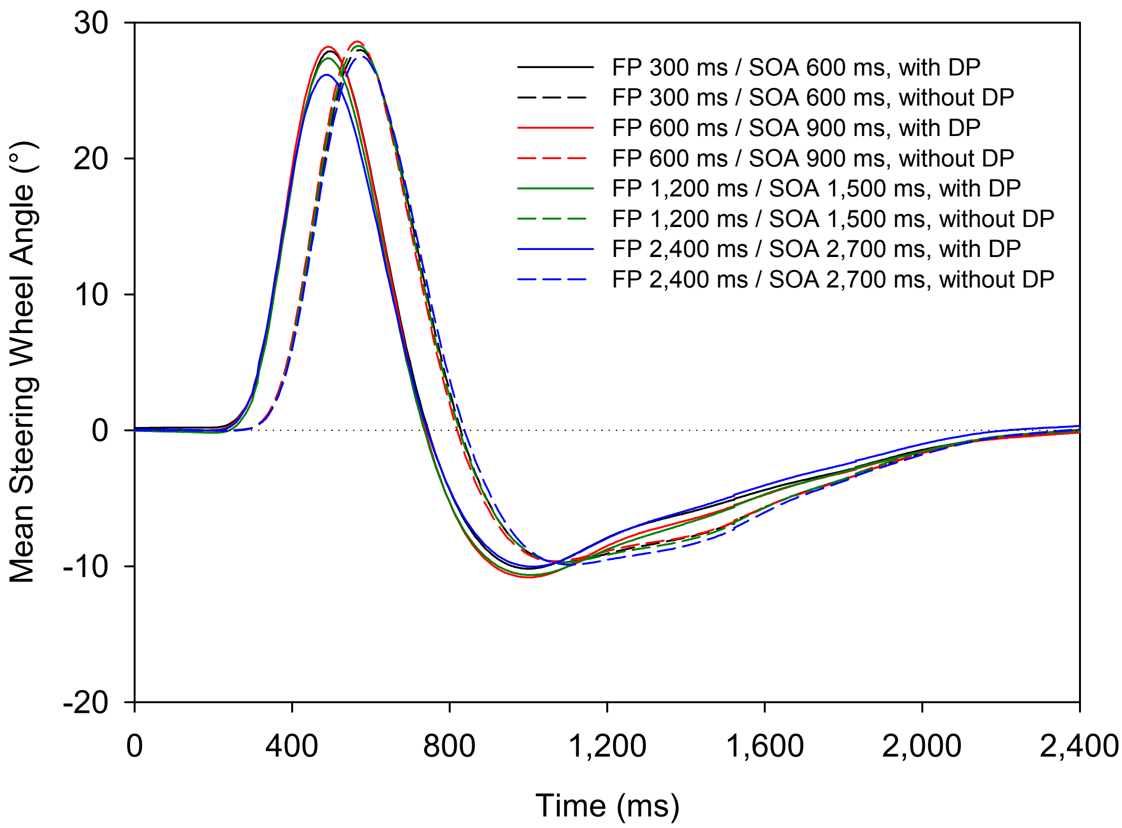

Figure 19: Results of Experiment 3 for the steering wheel angle trajectory. Mean steering wheel angle (collapsed across lane change direction) as a function of FP/SOA and availability of the direction precue (DP). Onset of the imperative stimulus at Time = 0 ms.

Steering wheel velocity. The steering wheel velocity is illustrated in Figure 20. Its course largely reflects the observations that were made for the steering wheel trajectory.

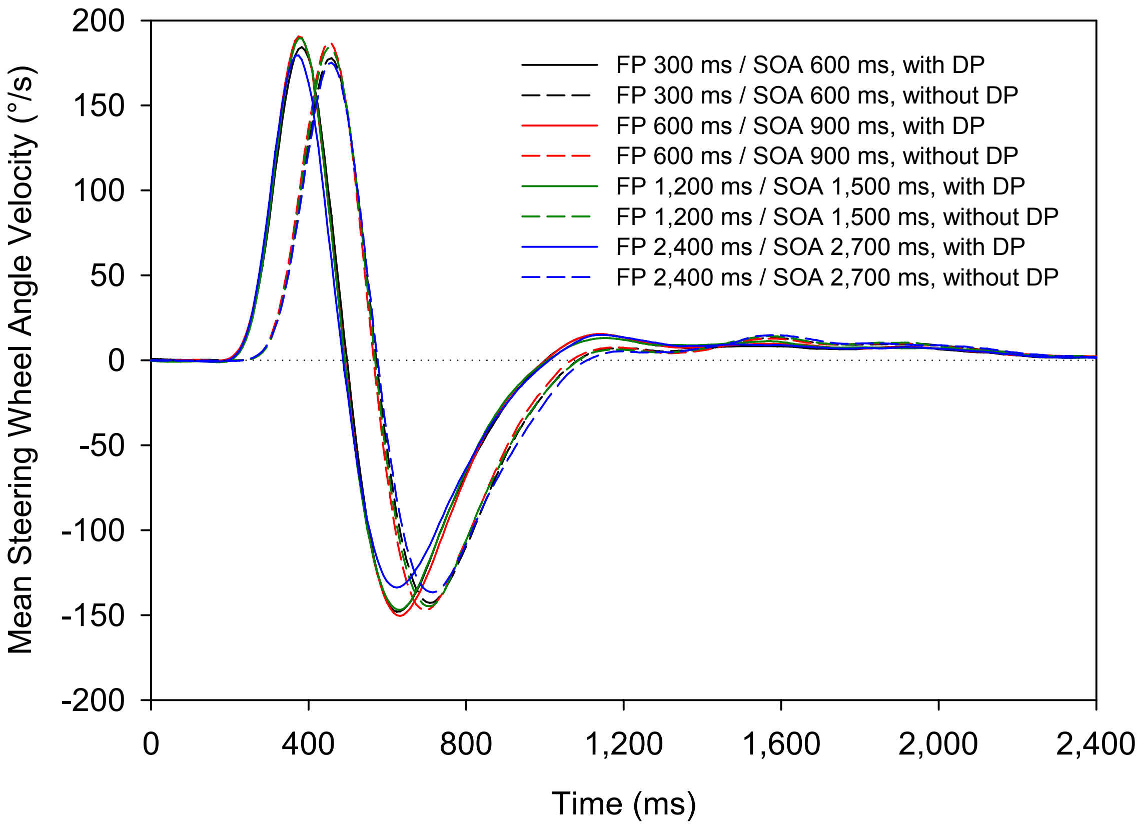

Figure 20: Results of Experiment 3 for the steering wheel angle velocity profile. Mean steering wheel angle velocity (collapsed across lane change direction) as a function of FP/SOA and availability of the direction precue (DP). Onset of the imperative stimulus at Time = 0 ms.

Initial steering wheel submovement

Time to peak steering wheel velocity (TTP1). The factors direction precue and direction exerted significant effects on TTP1 ($F(1,14) = 5.29$, $p < 0.05$, $\eta_p^2 = 0.27$ and $F(1,14) = 5.49$, $p < 0.05$, $\eta_p^2 = 0.28$, respectively). Lane changes with advance information on direction exhibited a slightly longer TTP (M = 128 ms, SD = 19 ms) than lane changes without it (M = 126 ms, SD = 17 ms). Lane changes to the left led to shorter TTPs (M = 125 ms, SD = 19 ms) than lane changes to the right (M = 129 ms, SD = 18 ms). No more significant effects were observed, but the factor FP showed a trend to significance ($F(3,42) = 2.64$, $p < 0.1$, $\eta_p^2 = 0.16$). This trend was based on the difference ($p < 0.1$) between TTP1 in the 600 ms FP (M = 128 ms, SD = 18 ms) and the 2,400 ms FP (M = 126 ms, SD = 18 ms).

Time after peak steering wheel velocity (TAP1). TAP1 was affected by the factors FP duration ($F(3,42) = 3.05$, $p < 0.05$, $\eta_p^2 = 0.18$) and direction precue ($F(1,14) = 14.30$, $p < 0.01$, $\eta_p^2 = 0.51$). Bonferroni-corrected pairwise comparisons showed a trend ($p < 0.1$) for longer TAPs in the FPs 300 ms (*M* = 105 ms, *SD* = 31 ms) and 1,200 ms (*M* = 105 ms, *SD* = 30 ms) than in the longest FP (*M* = 103 ms, *SD* = 29 ms). Trials with advance information on direction (*M* = 102 ms, *SD* = 29 ms) exhibited a shorter TTP1 than trials without it (*M* = 107 ms, *SD* = 30 ms).

Second steering wheel submovement

Time to peak steering wheel velocity (TTP2). The ANOVA yielded two main effects for the factors direction precue ($F(1,14) = 18.90$, $p < 0.01$, $\eta_p^2 = 0.57$) and direction ($F(1,14) = 10.05$, $p < 0.01$, $\eta_p^2 = 0.42$). Consistent with the shortening of TAP1, TTP2 was shorter for trials with direction precue (*M* = 273 ms, *SD* = 81 ms) than without it (*M* = 283 ms, *SD* = 85 ms). Lane changes to the left featured shorter TTPs (*M* = 273 ms, *SD* = 87 ms) than those to the right (*M* = 283 ms, *SD* = 79 ms). A trend towards significance was observed for the interaction between the factors FP duration and direction ($F(3,42) = 2.82$, $p < 0.1$, $\eta_p^2 = 0.11$).

Time after peak steering wheel velocity (TAP2). No effects on TAP 2 were observed for any factor.

Table 3: Overview of kinematic results in Experiment 3. Means (*M*) of kinematic variables and their standard deviations (*SD*) as a function of FP duration, direction precue and direction for initial and second steering phases. TTP: time to peak steering wheel velocity, TAP: time after peak steering wheel velocity. The indices 1 and 2 indicate the initial and the second steering wheel submovement.

Direction Precue:	with				without			
Direction	left		right		left		right	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				FP 300 ms / SOA 600 ms				
Initial steering wheel submovement								
TTP1 (ms)	125	20	131	20	124	19	130	17
TAP1 (ms)	102	29	103	29	107	33	109	32
Second steering wheel submovement								
TTP2 (ms)	267	85	281	81	275	88	290	83
TAP2 (ms)	368	158	392	167	394	140	401	154
				FP 600 ms / SOA 900 ms				
Initial steering wheel submovement								
TTP1 (ms)	127	19	132	21	125	19	128	17
TAP1 (ms)	102	30	104	29	105	30	106	28
Second steering wheel submovement								
TTP2 (ms)	272	83	280	77	279	92	287	78
TAP2 (ms)	371	154	358	148	401	156	390	149
				FP 1,200 ms / SOA 1,500 ms				
Initial steering wheel submovement								
TTP1 (ms)	126	20	131	19	124	18	129	15
TAP1 (ms)	102	31	103	28	106	30	108	31
Second steering wheel submovement								
TTP2 (ms)	271	89	279	76	279	89	288	84
TAP2 (ms)	410	160	374	147	407	152	387	149
				FP 2,400 ms / SOA 2,700 ms				
Initial steering wheel submovement								
TTP1 (ms)	125	19	128	19	124	18	126	18
TAP1 (ms)	99	30	101	28	107	33	106	28
Second steering wheel submovement								
TTP2 (ms)	263	85	274	76	282	90	283	79
TAP2 (ms)	381	159	374	155	404	149	388	133

Quality checks

Corrective movements. The ANOVA delivered a main effect for the factor FP duration (F(3,42) = 3.53, $p < 0.05$, $\eta_p^2 = 0.20$). Pairwise comparisons (corrected for multiple testing) showed that this effect originated from a trend to significance ($p < 0.1$) for the difference between the mean number of corrective movements in the shortest (M = 6.57, SD = 1.18) and the longest FP condition (M = 6.40, SD = 1.11). No other effects were observed.

Lateral deviation. The mean lateral deviation was significantly affected by the factors FP duration (F(1.87,26.13) = 5.09, $p < 0.05$, $\eta_p^2 = 0.27$) and direction (F(1,14) = 7.03, $p < 0.05$, $\eta_p^2 = 0.33$). Bonferroni-corrected pairwise comparisons revealed that the mean lateral deviation was closer to the starting lane in the shortest FP condition (M = 19.60, SD = 2.65) than in the 2,400 ms FP condition (M = 20.15, SD = 2.67, $p < 0.05$). Lane changes to the left (M = 20.30, SD = 2.70) were closer ($p < 0.01$) to the target lane than those to the right (M = 19.37, SD = 2.76).

Apart from these two main effects, an interaction between the factors FP duration and direction precue was observed (F(3,42) = 3.70, $p < 0.05$, $\eta_p^2 = 0.21$). Data was collapsed across the factor direction (see Figure 21) and four t-tests with Bonferroni-corrected significance level ($\alpha = 0.01$) were performed to test the differences between trials with and without advance information for each FP duration. Only in the 1,200 ms FP condition ($p = 0.04$), did mean lateral deviation from the starting lane tend to be larger for trials with advance information (M = 20.14, SD = 2.56) than for trials without advance information (M = 19.55, SD = 2.87).

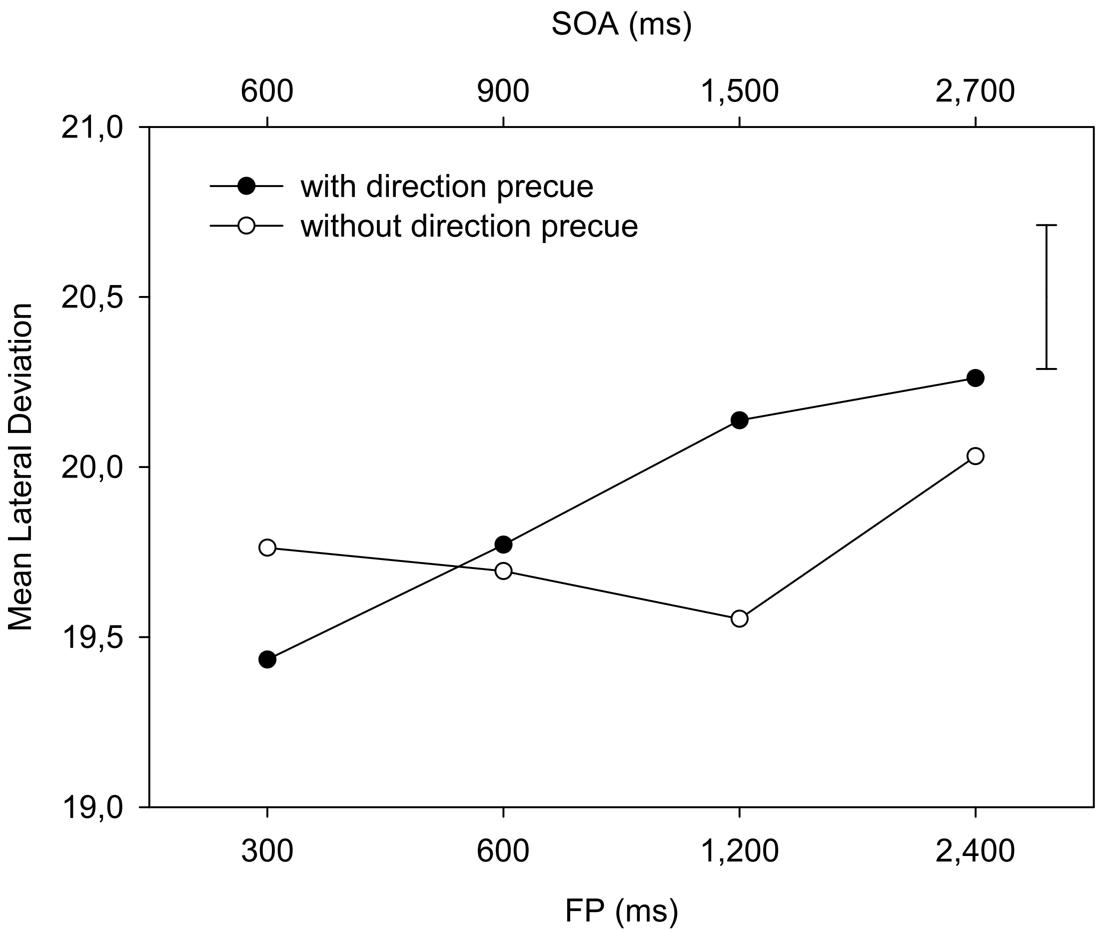

Figure 21: Results of Experiment 3 for the mean lateral deviation. Mean lateral deviation as a function of FP/SOA and availability of the direction precue. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002)

2.4.4 Discussion

In the third experiment it was expected that event-specific preparation might improve the preparation of the steering action. The second hypothesis consisted in the assumption that temporal advance information would exert its main influence in a medium FP, thus leading to a U-shaped RT-function. Finally, both mechanisms, temporal and event-specific preparation were expected to interact, as they were supposed to support the preparation of late processes (i.e., motor processes) in this specific task.

Reaction times. As expected, event-specific preparation was facilitated by the delivery of full advance information about the required lane change direction. Mean RTs were 70 ms shorter for trials with direction precue than for trials without it. This suggests that the direction precue information was efficiently processed by participants in preparing the next lane change. This absolute effect size is only slightly smaller than the absolute effect size of the factor direction precue in Experiment 1, which added up to 74 ms. The result is consistent with findings indicating the improvement of response preparation processes when movement parameters can be specified before the reaction (e.g., Hasbroucq et al., 1999; Leuthold et al., 1996; Müller-Gethmann et al., 2000; Rosenbaum, 1980). Of course, since the specific directional information modified the task from a two-choice reaction task to a simple reaction task, a 50% reduction in the number of alternatives in a task requiring only little cognitive transformation certainly contributed to the RT reduction (Goodman & Kelso, 1980). The precuing effect could be observed even though the FP between warning and imperative stimulus was varied randomly. An analogous result occurred in Spijkers and Steyvers (1984), who, in their second experiment, also confirmed a precuing effect in a variable FP paradigm. Interestingly and as observed in the first experiment of this thesis, the precuing effect was robust enough to be observed in a driving task that requires permanent attention. This is because the virtual vehicle had to be kept in the middle of the actual lane as best as possible. The participants thus deployed their spare cognitive resources for preparatory purposes. It remains an open question whether an enrichment of the driving task with augmented complexity, i.e., a higher cognitive load, would reduce the effectiveness of response preparation.

With respect to temporal preparation, the data was only partly consistent with the second hypothesis. As already seen in the second experiment, there were no differences between the shortest FP (300 ms) and the following two FPs (600 ms and 1,200 ms). However, optimal temporal preparation seemed to be possible only in the latter two medium FPs, since RTs in these two FPs were shorter than in the longest FP (2,400 ms). Compared with Experiment 2, the temporal range supporting optimal preparation was reduced from approximately 1 s (FP 300 ms to FP 1,200 ms) to 600 ms (FP 600 ms to FP 1,200 ms). This result may hint at a prolongation of the required preparation interval, when temporal advance information is enhanced by contextually helpful information. Alternatively, this observation could be regarded as a direct consequence of the design of the third experiment, which did not include the no FP condition. With the 300 ms FP, the expectancy of the imperative stimulus was possibly better supported in the second than in the third experiment, since in the second experiment participants also had to react without any temporal preparation. Consequently, even a short FP of only 300 ms might have been perceived as helpful for preparation. As was also observed in Experiment 2, the longest FP of 2,400 ms yielded longer RTs than the two preceding FPs. Time uncertainty seemed to increase with the longest FP, indicating a growing impairment of the prepared state of readiness.

Interestingly, the effect size of event-specific preparation was about three times higher than that of temporal preparation (η_p^2 = 0.94 vs. η_p^2 = 0.31). Obviously, this difference illustrates the predominance of contextual information over mere temporal preparation in this specific task. Nevertheless and in contrast to the findings of Spijkers and Steyvers (1984), an interaction between temporal and event-specific preparation was observed. The RT difference between full and no advance information was smaller in the shortest FP than in the longest FP. This difference could be interpreted as a disadvantage for long preparatory time intervals without contextual information. In other words, the availability of contextual information might contribute to an extended maintenance of the response readiness state that is mostly influenced (in typical cases) by temporal preparation. With respect to the AFM logic (Sternberg, 1969), the interactive relationship between event-specific and temporal preparation suggests that both processes affect the same stage in the (sequential) human information processing chain. As precise inferences about the concerned stage cannot be drawn here, it can only be assumed that a late motor stage might be the best candidate for this interactive effect. Based on the thoughts of Correa et al. (2006) the lane change task used in this study can be assumed to require mostly motor performance, so that any optimization processes were possibly directed at the motor stages. A possible reason for the different findings of Spijkers and Steyvers (1984) and the current experiment consists in the FP length and in the FP distribution. The mentioned authors deployed FPs of 3, 4 and 5 s, whereas the FPs in this study ranged from 300 ms to 2,400 ms. The relative differences between FPs of 3, 4 and 5 s (between 25% and 66%) are much smaller than those between 300, 600, 1,200 and 2,400 ms (between 100% and 400%), so that variance in temporal preparation might be increased to a greater extent in the latter FP distribution. Of course, another reason for the different results may be the different reactions that were required in the studies.

Kinematic variables. First of all, event-specific preparation shortened the length of TAP1 and TTP2, thus corroborating the hypothesis. Moreover and unexpectedly, it slightly lengthened the duration of TTP1. A further look at the effect sizes showed that the directional advance information exerted its main influence during TAP1 (η_p^2 = 0.51) and TTP2

($\eta_p^2 = 0.57$), whereas its effect on TTP1 was smaller ($\eta_p^2 = 0.27$). Keeping this weighting in mind, the shortening of the two kinematic phases around the first peak steering wheel angle seems to be the predominant effect of event-specific preparation, an effect that is in line with the results of the first experiment.

With regard to temporal preparation, only TAP1 was affected. Compared with the effect size of event-specific preparation in this phase ($\eta_p^2 = 0.51$), the effect of temporal preparation was rather small ($\eta_p^2 = 0.18$). This effect on TAP1 is not consistent with the results of Experiment 2, in which TTP1 was affected by temporal preparation. As a first tentative conclusion, this pattern of effects argues for generally predictable effects of event-specific preparation, whereas the effects of temporal preparation might not be that stable.

In order to qualify the lane change maneuvers in terms of accuracy and efficiency, the qualitative variables were considered. The number of corrective movements was not affected by event-specific preparation, speaking for qualitatively comparable lane change maneuvers, regardless which directional precue was administered. With regard to the mean lateral deviation, the shortest FP duration seemed to worsen the quality of the movement, at least when compared with the longest FP. This effect might be compared with the disadvantage in mean lateral position after the shortest FP in Experiment 2. Obviously, such a short FP is not sufficient to prepare a complex driving maneuver adequately, although RT is not significantly prolonged. The advantageous effect of temporal preparation on the vehicle position in the 2,400 ms condition seems to reflect an SAT effect: RT is worse than in the two preceding FPs, but the positional quality of the lane change is higher than in the shortest FP. Interestingly and as was observed in Experiment 2, this potential SAT effect is still detectable after the entire lane change steering movement is almost finished. Beyond that, FP and the precue information interacted to the extent that movement quality was especially good in the 1,200 ms FP when the precue delivered directional information. Thus, performance in terms of accuracy was most efficient when the preparatory period was rather long and the direction precue was available. Taken together with the RT data, the 1,200 ms FP yields the best results in this experiment.

As was also observed in the preceding experiment, lane change direction affected the kinematic variables, since lane changes to the left shortened TTP1 and TTP2. Interestingly the shortening of TTPs in lane changes to the left corresponded with a mean lateral deviation closer to the target position in lane changes to the left than in those to the right. This finding might be a hint supporting the argumentation that a shortening of MTs goes along with a higher efficiency of the lane change maneuver. Apart from this assumption, the directional effects will not be interpreted further since direction effects are quite common in driving experiments and seldom feature a regular and predictable effect (see e.g. Wallis et al., 2002).

Conclusion. In terms of RT effect size, Experiment 3 established a predominance of event-specific directional advance information over mere temporal information. Participants benefited most from directional precues, whereas temporal precues only led to small advantages in information processing. Interestingly, an interaction between both types of preparation emerged presumably indicating a common effect on the motor stage of the information processing chain. The kinematic results largely mirrored the results of the preceding two experiments, establishing benefits from event-specific preparation for response execution. These benefits were revealed by shortened kinematic movement phases around the first peak steering wheel angle. Temporal preparation did not exert clear effects on the kinematic variables and did not replicate the effect found in Experiment 2. Thus, it seems that temporal preparation indeed increases the general state of readiness, but does not necessarily support response execution. In fact, an SAT effect between RT and the accuracy of the mean lateral deviation of the vehicle indicated that variable FPs entail both benefits and costs.

2.5 Experiment 4: Movement Precuing and Temporal Preparation, Open Issues

The fourth experiment was designed in order to address open issues that arose from the RT analyses of the second and third experiment. These open issues consisted, on the one hand, in RT result patterns that were not really clear-cut, and, on the other, in methodological differences between Experiment 2 and 3.

2.5.1 Introduction

In the preceding Experiment 2 and 3, the RT function resulting from temporal preparation was somewhat unexpected since even the shortest FP of 300 ms delivered minimal (Experiment 2) or not statistically longer RTs (Experiment 3) than the following two medium FPs (600 or 1,200 ms). As was stated in the discussion of Experiment 2, a possible explanation for this observation might consist in the length of the effective preparatory period (Los & Schut, 2008). Since the precue was displayed for 300 ms in both experiments, the length of the effective preparatory interval until the imperative stimulus appeared added up to an SOA of 600 ms. As was observed by Bertelson and Tisseyre (1968), this time period can be considered sufficient for creating a temporally optimal state of readiness. Consequently, to reveal the expected U-shaped time course of temporal preparation in this lane change task, a shorter FP was required. In Experiment 4, this FP was implemented with a duration of 0 ms, i.e., the onset of the imperative stimulus followed the offset of the precue directly. This FP corresponds to an SOA of 300 ms. Since the precue itself was displayed for 300 ms again, the effective length of the temporal preparatory interval was half as long (namely 300 ms) as in the preceding Experiment 2 and 3. It was expected that this 0 ms FP should yield longer RTs than the subsequent medium FPs.

It was criticized in Experiment 3 that the time course of temporal preparation might not be comparable with the results of Experiment 2, since the no FP condition was neglected in Experiment 3. This modification of the FP distribution might have influenced the participants' temporal state of readiness, especially with regard to the shortest FP. For this reason, a no FP condition was reintroduced in the current experiment. It was expected that this condition should yield the longest RT compared with all other FPs, as was already observed before.

In Experiment 3 an interaction between the factors temporal preparation and event-specific preparation was observed. This effect was interpreted as an advantage for long preparatory intervals with event-specific information compared with those without event-specific information. Contextually helpful information was supposed to extend the temporal state of readiness. However, it remains unclear to what extent event-specific information might influence response preparation in its early temporal phase. This question was also addressed in the current experiment.

2.5.2 Method

Participants. Six females and six males with a mean age of 24.17 years (*SD* = 4.00 years, range = 19 to 33 years) participated in the experiment. All participants had normal or corrected-to-normal vision and were in possession of a driving license. The mean yearly driving experience of the participants added up to 5,717 km/year (*SD* = 6,536 km/year). Neither colour vision nor stereoscopic discrimination was impaired. All participants were right-handed.

Driving task, apparatus and stimuli. There were no differences between this experimental setup and that of the preceding experiment.

Procedure. There were only slight differences between the procedure in this experiment and that of the preceding experiment. The training procedures were absolutely comparable with Experiment 3, except that the second complete training block consisted of 36 trials. After the training blocks, 18 experimental blocks consisting of 36 trials each were run for each participant. Each experimental condition was repeated twice in one block. All trials were presented in random order. The experimental session lasted about 2 hours.

Experimental design. The experimental within-subject design was a nested design. For this experiment, the three factors FP duration (0, 300, 600, 2,400 ms), lane change direction (left vs. right) and direction precue (with vs. without precue) were crossed completely, resulting in 16 different conditions. In order to implement an additional condition without temporal and event-specific preparation, the factor FP duration was enhanced by a “no FP” level. Logically, this level could not be combined with the factor direction precue, as in this condition no precue was presented. Consequently, the combination of the no FP level with the factor direction (left vs. right) resulted in two additional conditions (see Table 4). The dependent variables were RT and error rates.

Table 4: Design of Experiment 4 (FP = foreperiod, SOA = stimulus onset asynchrony, LC = lane change, L = left, R = right, Y = yes, N = no).

Factor	Factor levels																	
FP / SOA	none		0 ms / 300 ms				300 ms / 600 ms				600 ms / 900 ms				2,400 ms / 2,700 ms			
LC direction	L	R	L		R		L		R		L		R		L		R	
Direction precue	/	/	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
No. of trials	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40

Data reduction and data analysis. Data reduction and the definition of RT and errors were equal to the preceding experiment. As the experimental design was a nested one, three Greenhouse-Geisser corrected repeated measures ANOVAs on mean RT as well as on error rates were performed. The first two two-way ANOVAs served especially to compare the no FP condition with any other FP duration. Thus, in these two analyses the factor FP duration with all five levels (no FP, 0, 300, 600, 2,400 ms) was combined with the factor direction, while the factor direction precue was either fixed to with precue or without precue. The third three-way ANOVA reduced the factor FP duration to the four FP conditions 0, 300, 600 and 2,400 ms and combined it with the two factors direction and direction precue.

2.5.3 Results

Error rates. As in the preceding Experiment 3, error rates were generally low in this experiment. 3.54% of all trials had to be discarded due to errors. Anticipations formed the largest part of this sum and totaled to 2.62% of all trials. In 0.66% of all trials, the participants changed by more than one lane. RTs were too long (misses) in 0.21% of all trials. In 0.05% of all trials, the participants left the drivable corridor. In 0.01% of all trials, lane changes were performed in the wrong direction.

Effects of the experimental factors were only observed for anticipations. The first ANOVA yielded a main effect for the factor FP duration ($F(4,44) = 12.04$, $p < 0.01$, $\eta_p^2 = 0.52$). Bonferroni-corrected pairwise comparisons performed post-hoc showed that trials without precue (no FP condition) did not lead to any anticipatory reaction. For any other FP duration, the error rates were higher (0 ms: M = 0.30%, SD = 0.35%, $p < 0.05$; 300 ms: M = 0.60%, SD = 0.69%, $p < 0.05$; 600 ms: M = 1.00%, SD = 1.04%, $p < 0.05$; 2,400 ms: M = 1.00%, SD = 1.39%, $p < 0.1$). The second ANOVA confirmed the main effect of FP duration also in trials without advance information on lane change direction ($F(2.23,24.48) = 5.97$, $p < 0.01$, $\eta_p^2 = 0.35$). But in this case, pairwise comparisons revealed a higher rate ($p < 0.05$) of anticipations only in the longest FP (M = 0.30%, SD = 0.69%) compared with the no FP condition.

The third ANOVA that combined all three factors FP duration, direction precue and lane change direction while neglecting the no FP condition, revealed main effects for FP duration ($F(1.86,20.62) = 3.65$, $p < 0.05$, $\eta_p^2 = 0.25$) and the direction precue ($F(1,11) = 47.68$, $p < 0.01$, $\eta_p^2 = 0.81$). A post-hoc contrast ($F(1,11) = 5.72$, $p < 0.05$, $\eta_p^2 = 0.34$) on the FP duration main effect confirmed that the effect was a consequence of a difference between the 0 ms (M = 0.20%, SD = 0.69%) and the 2,400 ms (M = 0.60%, SD = 1.04%) FP duration. The longest FP led to more anticipations than the shortest FP. There were more anticipations when the directional precue was presented (M = 0.70%, SD = 0.68%) than when it was absent (M = 0.10%, SD = 0.17%).

Reaction times. Figure 22 illustrates the mean RT values analyzed in the following two ANOVAs. The first ANOVA on mean RT analyzing all trials with advance information on lane change direction revealed a main effect of FP duration ($F(1.77,32.98) = 97.70$, $p < 0.01$, $\eta_p^2 = 0.90$). Four planned t-tests revealed that the no FP condition (M = 480 ms, SD = 70 ms) led to longer RTs ($p < 0.01$ for each t-test) than any other FP duration (0 ms: M = 350 ms, SD = 47 ms, 300 ms: M = 321 ms, SD = 36 ms, 600 ms: M = 325 ms, SD = 32 ms, 2,400 ms: M = 350 ms, SD = 43 ms).

This main effect was also confirmed by the second ANOVA, which analyzed all trials without advance information on lane change direction ($F(1.55,32.35) = 58.35$, $p < 0.01$, $\eta_p^2 = 0.84$). Post-hoc planned t-tests indicated a slower reaction in the no FP condition than for any other FP duration (0 ms: M = 385 ms, SD = 47 ms, 300 ms: M = 377 ms, SD = 37 ms, 600 ms: M = 381 ms, SD = 42 ms, 2,400 ms: M = 402 ms, SD = 49 ms).

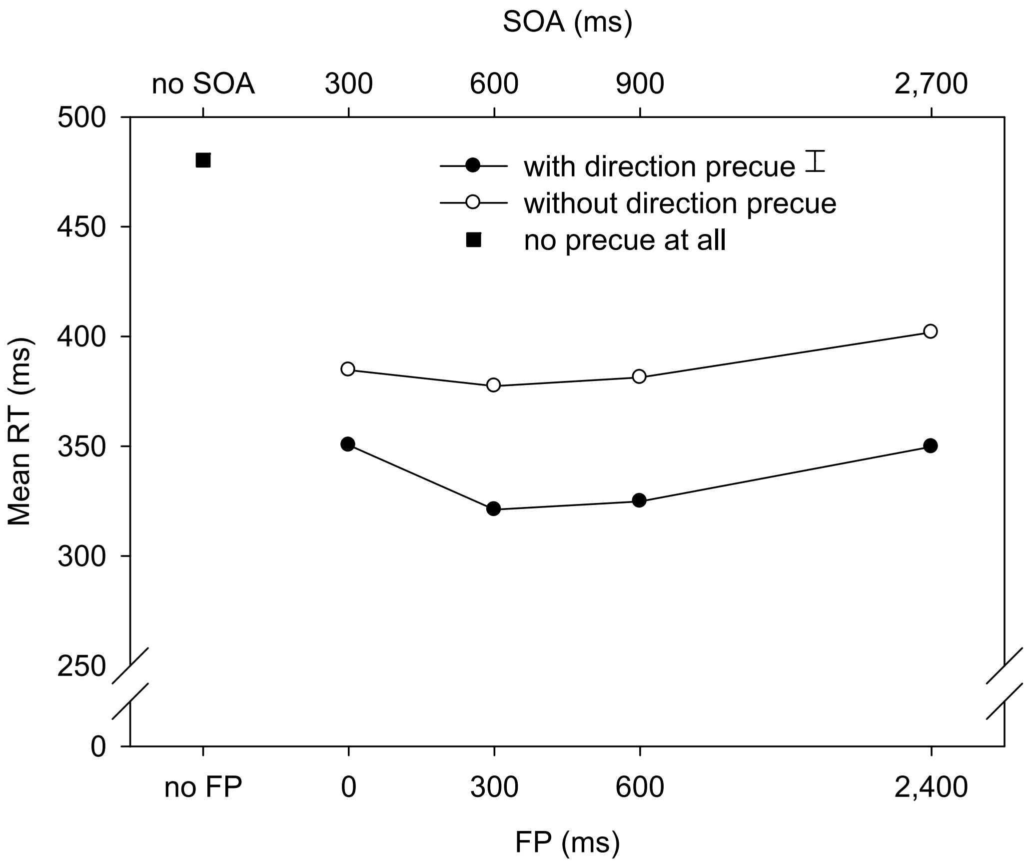

Figure 22: Results of Experiment 4 for temporal and event-specific preparation. Mean RT as a function of FP/SOA and availability of the directional precue. The data was collapsed across lane change direction. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

As stated above, the third ANOVA neglected the no FP condition and, instead, integrated the third factor, i.e., advance information on lane change direction. The ANOVA yielded main effects for each factor. The main effect for FP duration ($F(3,33) = 9.89$, $p < 0.01$, $\eta_p^2 = 0.47$) was analyzed in detail by post-hoc Bonferroni corrected pairwise comparisons. These comparisons showed that the 300 ms FP ($M = 349$ ms, $SD = 36$ ms) yielded shorter RTs ($p < 0.05$ and $p < 0.01$ respectively) than the 0 ms ($M = 368$ ms, $SD = 46$ ms) and the 2,400 ms FP ($M = 376$ ms, $SD = 46$ ms). In addition, the 600 ms FP delivered shorter RTs ($p < 0.01$) than the 2,400 ms FP. The main effect for advance information on lane change direction ($F(1,11) = 113.89$, $p < 0.01$, $\eta_p^2 = 0.91$) indicated that RTs for trials with advance information ($M = 336$ ms, $SD = 38$ ms) were 50 ms shorter than for trials without advance information ($M = 386$ ms, $SD = 43$ ms). The third main effect for lane change direction ($F(1,11) = 8.45$, $p < 0.05$, $\eta_p^2 = 0.43$) revealed that lane changes to the right were performed slightly faster (M = 359 ms, SD = 39 ms) than lane changes to the left (M = 364 ms, SD = 40 ms).

Eventually, an interaction between the factors FP and direction precue ($F(3,33) = 13.79$, $p < 0.01$, $\eta_p^2 = 0.56$) emerged. To understand this interaction, the data was first collapsed across the directional factor. Then the differences between trials without advance information on lane change direction and trials with such information were calculated for each FP duration. Six t-tests (each difference was tested against each other) for dependent samples were computed. The significance level was reduced to $\alpha = 0.008$ in order to account for multiple testing. These tests revealed that the RT difference between trials without advance direction information and trials with such information was smallest in the 0 ms FP condition (M = 24 ms, SD = 20 ms) compared with all other FP conditions ($p < 0.008$ for each comparison; 300 ms: M = 56 ms, SD = 16 ms, 600 ms: M = 57 ms, SD = 20 ms, 2,400 ms: M = 52 ms, SD = 17 ms).

2.5.4 Discussion

The fourth experiment was conducted to address open issues resulting from the Experiment 2 and 3. It was hypothesized that the introduction of the shortest FP (0 ms, SOA 300 ms respectively) would finally reveal the typical time course of temporal preparation, i.e., a decrease of RT from the shortest FP to minimal RTs in medium FPs. In addition, it was expected to reveal further details about the interaction between event-specific and temporal preparation in short FPs. A replication of the interaction in long FPs, i.e., a slower fading of the state of readiness with advance information compared with the absence of advance information, was intended as well.

Anticipations were generally favoured by directional precues. This effect seems to be trivial, since mere temporal preparation or even no precue at all did not provide any information about where to steer, so that lane keeping was the logical behavioural consequence until the imperative stimulus appeared. Anticipations were also registered for the longest FP. One might argue that anticipations speak for a higher state of readiness since the motor reaction could no longer be inhibited. But this explanation is unlikely, since mean RTs were significantly longer in the longest FP than in the two preceding medium FPs. Thus, the state of readiness was probably lower in the longest FP. Alternatively, participants might have tried to time their reactions to the longest FP. The FP gap between 600 ms and 2,400 ms was quite large, so that the state of temporal preparation might have faded away and then reappeared. With regard to the time required for rebuilding this state of readiness, a gap of 1,800 ms might be sufficient (Alegria, 1974). However, due to the higher difficulty to estimate long FP durations, perfect timing becomes more difficult in the longest FP. Anticipations might have resulted from these imperfect timing attempts.

As could be expected, participants had a benefit from any kind of preparation, since mean RTs were significantly shorter in any event-specific or temporal preparation condition than in the no FP condition. This result is in line with the literature on this topic (see e.g. Bertelson & Tisseyre, 1968; Müller-Gethmann et al., 2003). Advance information on the direction of the upcoming lane change shortened RT by 50 ms compared with lane changes with only temporal preparation. In general, this effect replicated the corresponding findings of Experiment 1 and 3 and can be considered as a stable result. However, in the current experiment the absolute size of this effect was about 20 ms smaller than the advantages seen in the preceding experiments, but still 12 ms larger than the corresponding effect observed by Spijkers and Steyvers (1984). Consequently, the effect of contextual helpful information such as direction emerges to be highly useful in this driving task. The intuitive reason for this assumption might be that directional information is the most crucial navigational information in driving, whereas it is not that relevant in a basic experimental task, such as a sliding movement. One might hypothesize that the size of the RT benefit for directional information varies according to the task demands and to the relevance of the information for successful task fulfilment (cf. Correa et al., 2006 for temporal preparation).

As was hypothesized, a decrease of RTs from the shortest FP (0 ms) to the optimal FP of 300 ms was observed. This decrease was modest (19 ms in absolute size) and cannot be compared with the sharp decreases that are typically found for even shorter FPs (Müller-Gethmann et al., 2003). However and contrary to the findings in Experiment 2 and 3, the idea of Näätänen (1970) that RT will not be shortest in the shortest FP was confirmed. Since RTs increased with the longest FP, in this experiment a basically U-shaped RT function was approximated, although increases and decreases were only moderate in size. One might therefore come to the conclusion that the selection of short FPs was responsible for the absence of this basic effect in Experiment 2 and 3. Nevertheless, it has become apparent that an effective temporal preparatory period (SOA in this case) of only 600 ms yields minimal RTs in this driving task. Compared with findings from basic experiments, this time period is longer than optimal FP durations in static and discrete experimental settings. Müller-Gethmann et al. (2003) found a FP of 200 ms (SOA 270 ms from precue onset to the onset of the imperative stimulus) to be optimal; Bertelson and Tisseyre (1968) suspected a FP of only 100 ms (the effective duration of the preparatory interval, i.e., the SOA, was probably also 100 ms, since the warning stimulus was a short auditory click) to be sufficient to create an optimal state of readiness. Seen from this angle, permanent monitoring and control of the vehicle position, the presence of contextual information and the different motor reactions seem to slow the cognitive processing of temporal precues by a factor of approximately 2 to 6. With regard to a real and much more complex driving scenario, this result can be seen as an indication of a considerable lengthening of the time period required until temporal precues are processed.

As in the preceding experiment, an interaction between temporal and event-specific preparation was observed. In the current experiment, the interactional effect was located in the shortest FP condition, since in this condition the difference between trials with advance information and without it was smaller than in all subsequent FPs. Thus, although advance information on lane change direction already seems to be available and operative after 300 ms, it does not show its full effect until an effective preparatory interval of 600 ms. Unexpectedly and contrary to the observation in Experiment 3, FP durations longer than 300 ms did not further influence the RT difference between trials with or without advance information. Thus, the interpretation that contextually helpful information might extend the temporal state of readiness to longer FPs is compromised. So far, this interaction seems to be unstable and difficult to replicate. Still, Experiment 3 and 4 deliver hints for existing interactions between temporal and event-specific preparatory processes. In this context, a step "backwards", i.e., away from the applied setting and into the field of basic research, might suffice to further analyze these processes.

2.6 Experiment 5: Response Priming

After having treated open issues in an additional fourth experiment, the thesis returns to its original plan, i.e., to implement another basic research paradigm into the lane change task: the response priming paradigm (Larish & Frekany, 1985; Rosenbaum & Kornblum, 1982). This paradigm was chosen to find out if effects of response preparation in the driving task (on RT level as well as on the kinematic level) would be corroborated by another methodological approach. Moreover, the response priming paradigm is suited to assess negative effects of response preparation, i.e., the costs of preparation, and thus opens a wider perspective on this topic.

2.6.1 Introduction

Research has shown that degraded alarm reliability can significantly impact operator performance (Cummings et al., 2007). Bliss and Acton (2003) investigated the effects of different alarm reliabilities (50%, 75% and 100%) on driver performance in a collision avoidance scenario. Their participants were asked to drive at constant speed on a highway in a fixed-base simulator. During the drive, collision avoidance alarms were emitted and the drivers had to check their correctness. Following a true alarm, they had to swerve to avoid being struck from behind by the approaching car. As was found and expected, decreasing alarm reliability degraded the evasion maneuver appropriateness and also lowered the alarm reaction frequency. But, interestingly, 100% reliable alarms had reaction costs in terms of higher collision rates than 50% reliable alarms. The authors attributed this unexpected effect to a routine reaction in the perfectly valid condition that led to an inattentive swerving maneuver. Moreover, drivers seemed to be more startled by true alarms, which also negatively affected collision rates in the 100% reliable alarm condition. This study is an example of the benefits and costs of response preparation in an applied context, especially since the observed costs were counterintuitive and contrary to the intended positive collision avoidance effect. Designers and engineers who develop such collision avoidance systems face a constant dilemma: ensuring early detection while avoiding false and irritating alarms (Parasuraman, Hancock, & Olofinboba, 1997).

Lee and See (2004) point out that trust in automation is not exclusively determined by system reliability, but also by factors such as timing, consequence and expectations associated with automation failures. Nonetheless, the reliability of any in-vehicle alert system is crucial for its effectiveness. Studies on alarm reliability give an impression of the costs of false alarms, since subsequent reactions on true alarms are degraded. This degradation is mainly the consequence of reactions that do not take place in case of a true alarm, since drivers do not trust anymore in the warning delivered by the system. Nevertheless, even imperfect systems may support driver performance in critical situations, since drivers may be able to distinguish true from false alarms (Maltz & Shinar, 2004).

However, it remains unclear how an actual false alarm degrades driving performance: A false alarm prepares for an action that is not required eventually. Thus, any reaction prepared by the driver has to be stopped as soon as he detects that the warning was not justified. In the context of collision warning systems, the understanding and interpretation of the false alarm is crucial: Collision warning systems that trigger open-loop responses might undermine safety by triggering inappropriate braking responses, thus compromising other motorists. Collision warning systems that redirect attention might generate closed-loop responses, allowing the driver to modulate the braking response according to the surrounding traffic (J. D. Lee et al., 2002). Still another issue is generally not addressed by studies on in-vehicle alarm reliability: What happens in case of a misleading alarm issued by the system, e.g., preparing a driver to speed up although braking would be required? Such a scenario in a collision avoidance study with spatially distributed alarms would incorporate a condition whereby a vehicle approaching from behind is detected, but misleadingly announced as approaching from the left. In such a case, the driver might be prepared to brake to let the other vehicle, supposedly coming from the left, cross in front of him. Despite this preparation, the driver will have to speed up and swerve as soon as he detects the other vehicle approaching from behind instead of from the left. This scenario exemplifies a situation in which a response not only has to be inhibited; it also has to be reprogrammed and replaced by another response. Such sudden changes of a prepared reaction pattern in driving can be considered ubiquitous. For example, when drivers rely on preparatory information from navigational systems and are suddenly surprised by construction work blocking the intended path. It can be expected that misleading system information creating inappropriate preparation can induce additional response preparation costs.

In cognitive psychological research, the response priming paradigm (Larish & Frekany, 1985; Rosenbaum & Kornblum, 1982) deals with the benefits and costs of response preparation. As was explained in the general introduction, in the response priming paradigm a certain prime prepares the subject for a certain response that will be required with high likelihood, whereas in some cases another response that was not announced by the prime will be demanded. In the latter case, it is assumed that preparation is costly in terms of increased RT, since any prepared response has to be inhibited and the unexpected response needs to be programmed on the fly (Larish & Frekany, 1985; Lépine et al., 1989; Leuthold, 2003). The typical result of response priming studies consists of the validity effect. It implies decreased RTs for valid trials, increased RTs for invalid trials and medium RTs for neutral trials. As far as the author is aware, the response priming paradigm has not yet been implemented into a driving task such as the adapted lane change task deployed in this study. Thus, it is an open question whether this paradigm proves to deliver comparable results, i.e., a validity effect, in an applied driving context. If so, the response priming paradigm might promise to be a helpful tool for the evaluation of negative preparation effects elicited by different IVIS.

To this end, Experiment 5 examined the following hypothesis. It was expected that the valid announcement of lane change direction would lead to shorter RTs for the upcoming lane change maneuver than the neutral (i.e., temporal) lane change announcement. The latter one in turn was expected to feature shorter RTs than trials with invalid lane change direction announcement. Such a validity effect in a basic driving task would support the general hypothesis of this study that response preparation can be triggered in a low-level control task. It would further underpin the generalizability of theoretical and practical accounts on motor control to the applied context of driving.

With regard to the kinematic movement analysis, a favourable effect of the valid condition on response execution was expected. Presumably this advantage could be revealed by a result pattern that mimics the potential RT validity effect. Since response priming also represents an event-specific type of preparation, it was assumed that the general shortening of the kinematic phases around the first turning point of the steering movement, as observed in Experiment 1 and 3, could be replicated. This result would further underpin the applicability of the movement integration-hypothesis (Adam et al., 2000) to steering wheel movements.

2.6.2 Method

Participants. 14 subjects took part in Experiment 5. One participant had to be eliminated from data analysis since his data record was not complete due to technical problems during the experiment. Another participant had to be excluded as his data showed a strong trend to anticipatory reactions in the valid experimental conditions: 44% of all valid trials of this participant were identified as anticipations. The final sample consisted of 12 participants, half of them female, with a mean age of 25.25 years (*SD* = 3.65 years) and a mean yearly driving experience of 8,793 km/year (*SD* = 7,876 km/year). 9 participants declared by self-report to be right-handed, 2 were left-handed and 1 participant claimed to be ambidextrous. Neither colour vision nor stereoscopic discrimination was impaired.

Driving task, apparatus and stimuli. The same driving task as described in the general methodological introduction was deployed for the response priming experiment. As in the preceding experiments, primes were displayed in red colour and imperative stimuli in green colour. The stimuli used here were recruited from the first experiment. A valid or invalid prime was represented by a horizontal arrow pointing to the left or to the right. The neutral prime consisted only of the horizontal arrow shaft. With the exception of colour, the imperative stimulus corresponded exactly to the valid/invalid primes.

Procedure. The instruction was adapted to the response priming paradigm. The participants were told that the arrow prime would predict the lane change direction correctly in the majority of all trials having an event-specifically meaningful (i.e. not neutral) prime. They were asked to optimally prepare the upcoming lane change according to the prime information and to react as fast as possible to the subsequent imperative stimulus. The participants were unaware about the exact relation of validly to invalidly primed trials which was set to 75:25. In the case of a temporally primed, i.e., neutral trial, they were asked to remain uncommitted with regard to the lane change direction, but to generally prepare for the upcoming maneuver. Apart from that participants were required to always keep the virtual vehicle optimally in the middle of the actual lane.

In a first training block, participants were encouraged to try out the vehicle behaviour as well as to react appropriately to the imperative stimuli. This training block was cancelled when it was obviously clear to the investigator that the participant had gained a correct understanding of the task. Then a complete training block with 32 trials was administered in order to establish the same level of training among all participants. The training blocks were discarded from data analysis. The following single driving session lasted about 2 hours and consisted of 25 blocks. Within each block of 32 trials, each experimental condition was presented in random order. The distribution of valid, invalid and neutral trials in each block corresponded to the general distribution of trials described in Table 5. After each block, participants received feedback concerning their mean RTs and information about the percental change of the actual mean RT compared with the mean RT of the preceding block. Participants could determine the length of the break between blocks autonomously by starting the next block of trials via the PC keyboard.

Each trial started with an interval of 800 + X ms in which X was a random variable that followed an exponential distribution with a mean of 1 s. At the end of the interval, the prime (an arrow pointing to the left or to the right or a horizontal arrow shaft without arrowhead) was displayed for 300 ms. After prime offset, a fixed FP of 1,200 ms was implemented before the imperative stimulus (an arrow pointing to the left or to the right) was presented for 300 ms. A final interval of 3,500 ms was added to let the participant change the lane.

Experimental design. The design of this experiment was a univariate 3×2 within-subjects design. The first factor determined the validity of the prime. It consisted of the factor levels neutral (temporal), valid and invalid prime. In trials with a neutral prime, no direction at all was announced since the prime consisted only of a horizontal bar without arrow top. A valid trial was defined as a trial in which the arrow direction of the prime (left vs. right) was identical with the arrow direction of the imperative stimulus. In invalid trials the prime arrow announced a direction opposite from what was finally required by the imperative stimulus. The second factor was the lane change direction, i.e., left or right. As illustrated in Table 5, neutral primes were presented in 50% of all trials. Valid and invalid trials were given in the other 50% of all trials (see Larish & Stelmach, 1982), in proportions of 75% and 25% respectively.

Table 5: Design of Experiment 5 (LC = lane change, L = left, R = right).

Factor	Factor levels					
Prime validity	neutral		valid		invalid	
Prime direction	/	/	L	R	R	L
LC direction	L	R	L	R	L	R
No. of trials	200	200	150	150	50	50

Data reduction and data analysis. Data reduction corresponded to the general proceedings. For the statistical analysis, data was collapsed across the directional prime factor. The mean values entered into the ANOVA were therefore not based on the same cell frequencies, as can be concluded from Table 5. Error rates and mean RTs were submitted to a respective two-way repeated measures analysis of variance with prime validity (valid, invalid, neutral) and lane change direction as factors (left, right). In accordance with the preceding experiments, analogous ANOVAs were calculated for the kinematic variables.

2.6.3 Results

Error rates. 3.20% of all trials were eliminated from data analysis due to errors. This sum of errors was made up of anticipations (2.08%), lane changes by more than one lane (0.90%), lane changes into the wrong direction (0.11%) and misses (0.11%). Only anticipations were further analyzed since cell frequencies of the other error categories were too low to be analyzed meaningfully. The ANOVA of the anticipations yielded a significant main effect of prime validity ($F(1.21,13.27) = 9.49$, $p < 0.01$, $\eta_p^2 = 0.46$). Pairwise comparisons conducted post-hoc confirmed that valid trials led to more ($p < 0.01$ and $p < 0.05$, respectively) anticipations ($M = 2.0\%$, $SD = 2.77\%$) than invalid trials ($M = 0.10\%$, $SD = 0.34\%$) and trials with neutral primes ($M = 0.10\%$, $SD = 0.34\%$).

Reaction times (relative RT criterion). The ANOVA (see Figure 23) revealed that the main effect of prime validity was significant ($F(2,22) = 27.59$, $p < 0.01$, $\eta_p^2 = 0.72$) as was the main effect of lane change direction ($F(1,11) = 4.89$, $p < 0.05$, $\eta_p^2 = 0.31$). Post-hoc pairwise comparisons with Bonferroni-correction for multiple testing showed that valid trials led to shortest RTs ($M = 306$ ms, $SD = 49$ ms). These mean RTs were shorter ($p < 0.01$) than RTs in invalid trials ($M = 369$ ms, $SD = 24$ ms) and they were shorter ($p < 0.01$) than RTs in trials with neutral, i.e., temporal primes ($M = 347$ ms, $SD = 44$ ms). In addition, invalid trials featured the longest RTs. These were significantly longer ($p < 0.05$) than RTs in trials with neutral primes. With regard to lane change direction, lane changes to the left were initiated slower ($M = 345$ ms, $SD = 38$ ms) than lane changes to the right ($M = 337$ ms, $SD = 37$ ms). No interaction was observed between prime validity and lane change direction.

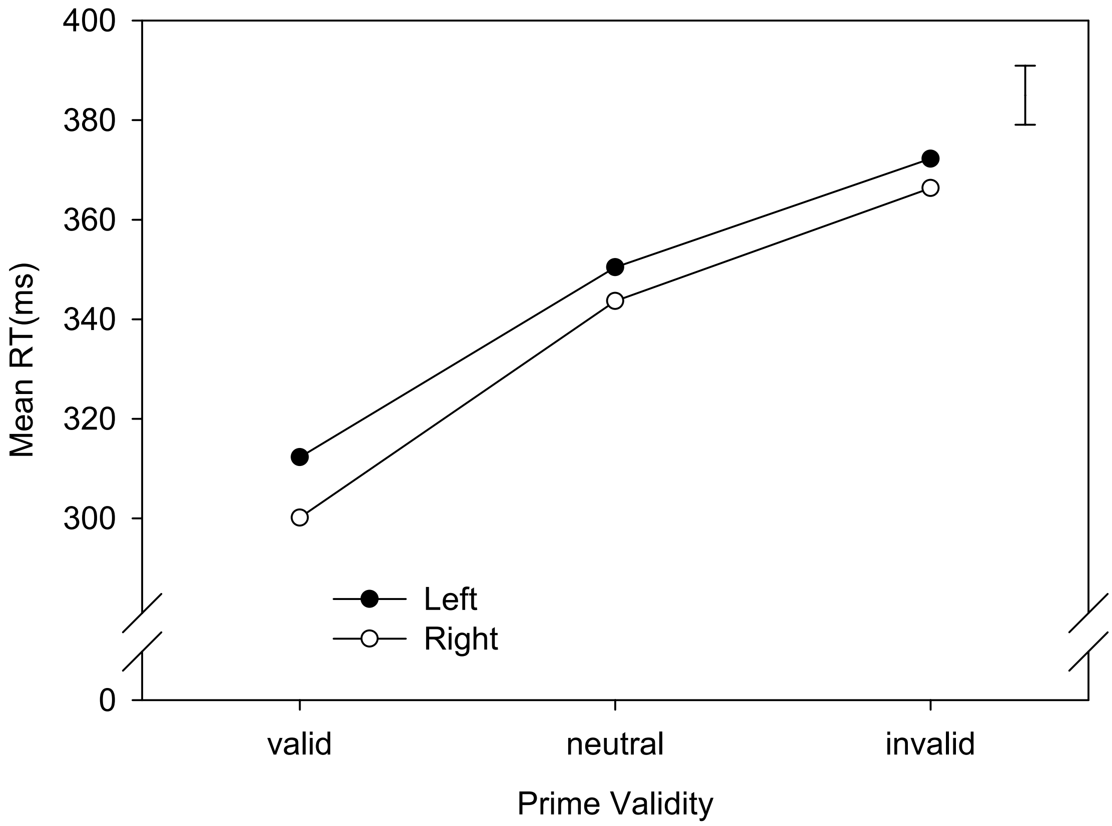

Figure 23: Results of Experiment 5 for response priming. Mean RT as a function of prime validity and lane change direction. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

Kinematic variables.

Steering wheel angle trajectory. The graphical illustration (Figure 24) of the steering wheel angle trajectory shows marked differences between the three priming conditions. The visual inspection indicates an earlier steering movement onset for valid trials than for neutral trials. However, the trajectory shape of valid trials and neutral trials seems to be quite comparable. With regard to invalidly primed trials, the trajectory shape reveals an initial clear deviation in the wrong direction up to approximately 3°. Only afterwards is the steering wheel angle corrected and redirected toward the correct movement direction. As is also clearly visible from Figure 24, the first peak of the trajectory is higher for invalidly cued trials than for validly cued trials or neutrally cued trials. This possibly results from a compensatory reaction to the initial incorrect deviation.

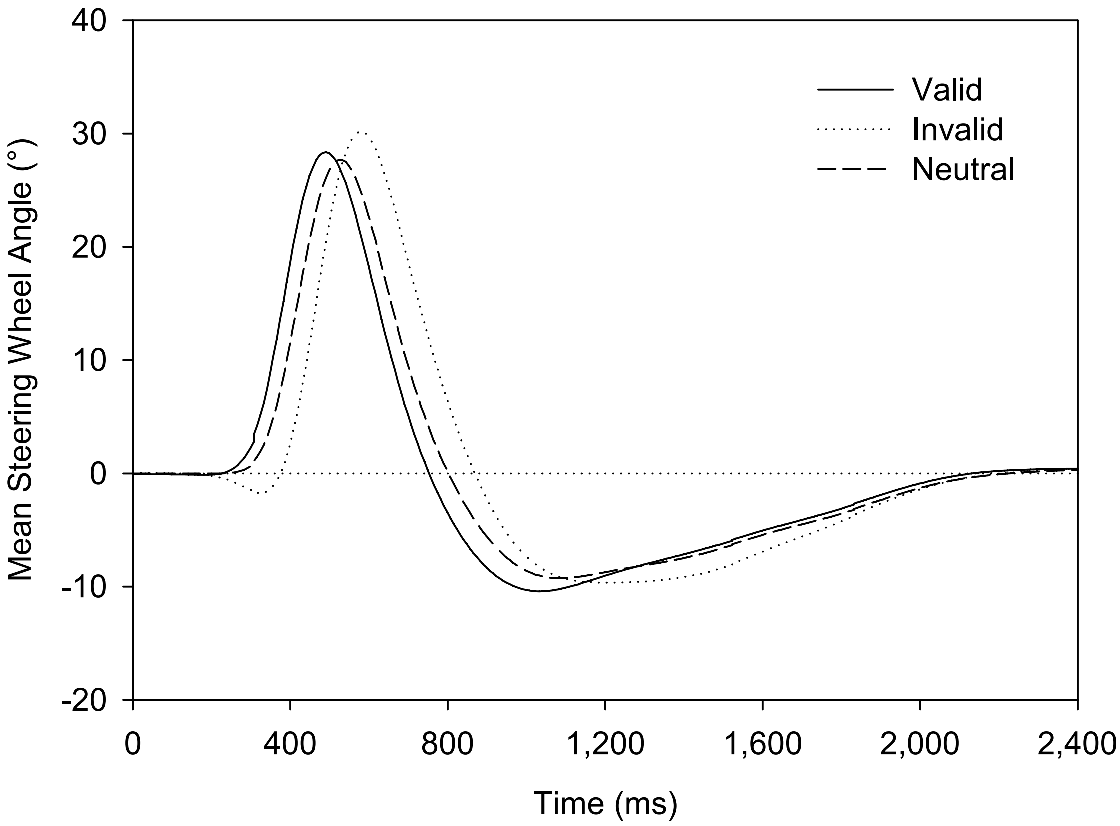

Figure 24: Results of Experiment 5 for the steering wheel angle trajectory. Mean steering wheel angle (collapsed across lane change direction) as a function of prime validity. Onset of the imperative stimulus at Time = 0 ms.

Steering wheel velocity. The steering wheel velocity profile also reflects the differences in movement onset as well as in the trajectory shapes (Figure 25). In addition, compared with the preceding experiments (see Figure 13, Figure 17 and Figure 20) it depicts the highest steering wheel angle velocities for invalidly primed trials, thus underlining the corrective character of the movement.

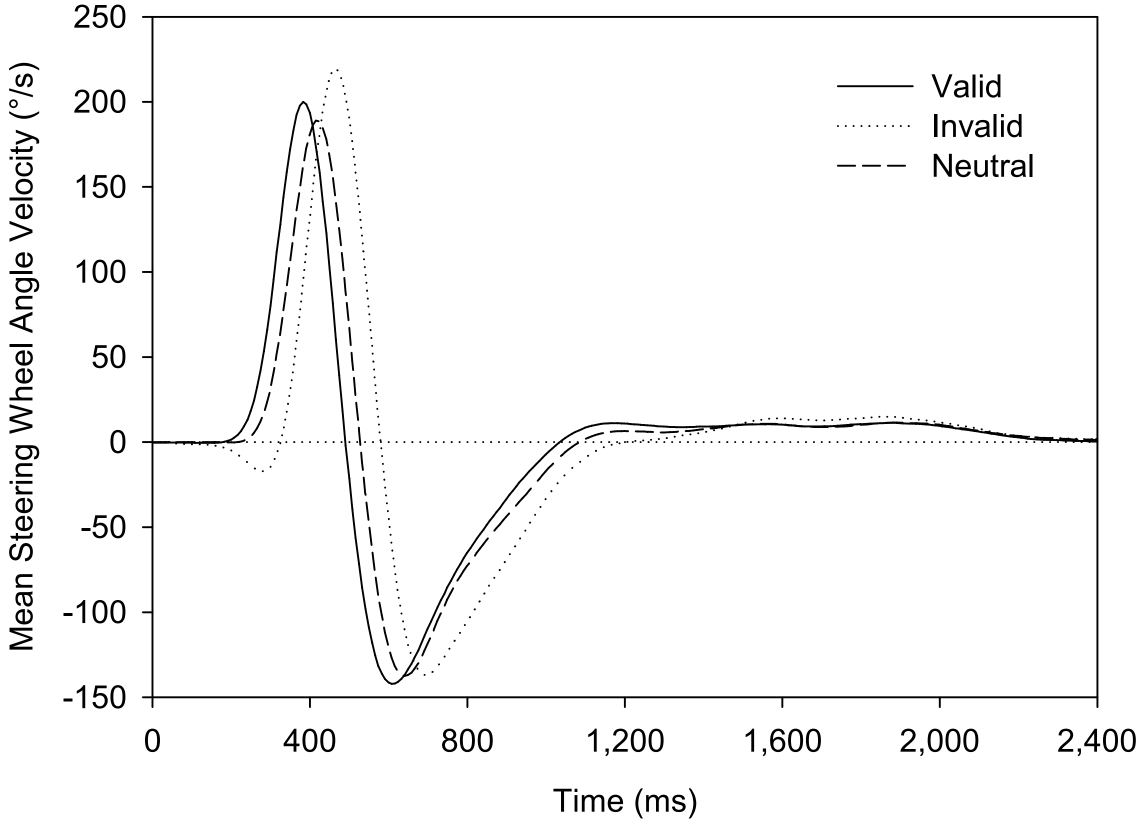

Figure 25: Results of Experiment 5 for the steering wheel angle velocity profile. Mean steering wheel angle velocity (collapsed across lane change direction) as a function of prime validity. Onset of the imperative stimulus at Time = 0 ms.

Initial steering wheel submovement. The results of the kinematic analyses are resumed in Table 6.

Time to peak steering wheel velocity (TTP1). The ANOVA revealed main effects of both experimental factors on TTP1. The effect of prime validity ($F(1.35,14.87) = 10.03$, $p < 0.01$, $\eta_p^2 = 0.48$) documented shorter TTPs in the valid ($M = 127$ ms, $SD = 22$ ms) and in the neutral precue condition ($M = 127$ ms, $SD = 21$ ms) than in the invalid precue condition ($M = 131$ ms, $SD = 22$ ms). The effect of lane change direction ($F(1,11) = 12.89$, $p < 0.01$, $\eta_p^2 = 0.54$) was reflected by shorter TTPs in lane changes to the left ($M = 125$ ms, $SD = 20$ ms) than in lane changes to the right ($M = 131$ ms, $SD = 24$ ms).

Time after peak steering wheel velocity (TAP1). TAP1 was affected by prime validity ($F(1,11.07) = 6.51$, $p < 0.05$, $\eta_p^2 = 0.37$). Bonferroni-corrected pairwise comparisons revealed that TAP1 was shorter ($p < 0.01$) in the valid ($M = 98$ ms, $SD = 34$ ms) than in the neutral prime condition ($M = 101$ ms, $SD = 34$ ms). Moreover, the valid prime condition tended to lead to shorter TAPs ($p < 0.1$) than the invalid prime condition ($M = 116$ ms, $SD = 38$ ms) did.

Second steering wheel submovement

Time to peak steering wheel velocity (TTP2). The ANOVA yielded a main effect for the factor prime validity ($F(1.01,11.11) = 5.31$, $p < 0.05$, $\eta_p^2 = 0.33$). According to the Bonferroni-corrected post-hoc test this effect was based on the trend to significance ($p < 0.1$) for the difference between validly ($M = 251$ ms, $SD = 90$ ms) and neutrally primed trials ($M = 255$ ms, $SD = 92$ ms). Although the descriptive difference between valid and invalid trials ($M = 289$ ms, $SD = 98$ ms) was larger, it failed to reach significance ($p = 0.11$).

Time after peak steering wheel velocity (TAP2). Although the ANOVA did not reveal a significant effect on TAP2, a trend to significance ($F(1.23,13.51) = 4.02$, $p < 0.1$, $\eta_p^2 = 0.27$) was observed for the factor prime validity.

Quality checks

Corrective movements. The mean number of corrective movements was influenced by the factor prime validity ($F(2,22) = 5.58$, $p < 0.05$, $\eta_p^2 = 0.34$). The participants corrected the steering wheel movement more often ($p < 0.05$) in neutrally primed ($M = 7.21$, $SD = 1.47$) than in invalidly primed trials ($M = 6.79$, $SD = 1.69$).

Lateral deviation. The mean lateral position after the end of TAP2 was affected by an interaction between the factors prime validity and lane change direction ($F(2,22) = 4.51$, $p < 0.05$, $\eta_p^2 = 0.29$). Three Bonferroni-corrected post-hoc t-tests showed that the mean lateral deviation differed only for lane changes to the right. The lateral position was worse in the neutral condition ($M = 17.64$, $SD = 2.41$) than in the valid condition ($M = 18.22$, $SD = 2.57$) and in the invalid condition ($M = 18.45$, $SD = 2.08$).

Table 6: Overview of kinematic results in Experiment 5. Means (*M*) of kinematic variables and their standard deviations (*SD*) as a function of prime validity and lane change direction for the initial and the second steering phase. TTP: time to peak steering wheel velocity, TAP: time after peak steering wheel velocity. The indices 1 and 2 indicate the initial and the second steering wheel submovement.

Validity	valid				neutral				invalid			
Direction	left		right		left		right		left		right	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Initial steering wheel submovement												
TTP1 (ms)	123	20	130	21	124	19	129	24	128	21	134	24
TAP1 (ms)	97	34	98	34	101	37	100	33	117	38	115	38
Second steering wheel submovement												
TTP2 (ms)	247	90	256	91	250	93	260	91	288	95	290	103
TAP2 (ms)	336	147	322	117	350	147	325	121	376	154	335	113

Additional PV and RT calculations. The visual inspection of both the mean steering wheel angle trajectory and the mean steering wheel angle velocity resulted in two possibly meaningful observations (see Figure 24 and Figure 25). First, invalidly primed trials exhibited a short negative deflection before participants apparently corrected their steering movement into the correct lane change direction. In these cases, the participants reacted twice, so that the RT calculation reported before only reflects the second RT, i.e., that of the movement into the correct direction. Second, invalidly primed trials seemed to exhibit a markedly higher peak steering wheel velocity during the initial steering wheel submovement than validly primed trials and neutrally primed trials. For these two reasons it seemed reasonable to confirm the difference in PV by an additional ANOVA. It also seemed plausible to apply an absolute RT criterion (+/-10°/s as cutoff for the steering wheel angle velocity instead of +10% of its PV) in order to account for the first movement in the wrong direction. To account for the potentially higher PVs (but not for the first movement into the wrong direction) RT was also calculated based on an absolute positive threshold (+10°/s). This last calculation allows the results of the relative RT threshold to be compared with an absolute threshold.

Peak steering wheel velocity (PV). The ANOVA for PV revealed a main effect of the factor validity ($F(1.19,13.11) = 11.13$, $p < 0.01$, $\eta_p^2 = 0.50$). Pairwise comparisons executed post-hoc showed that invalidly primed trials led to higher PVs (*M* = 315°/s, *SD* = 135°/s) than validly (*M* = 306°/s, *SD* = 133°/s, $p < 0.05$) or neutrally (*M* = 304°/s, *SD* = 131°/s, $p < 0.01$) primed trials. The effect of the factor direction showed a marked trend to significance ($F(1,11) = 4.83$, $p = 0.05$, $\eta_p^2 = 0.31$), indicating higher PVs for lane changes to the left (*M* = 315°/s, *SD* = 136°/s) than to the right (*M* = 303°/s, *SD* = 130°/s).

Reaction times (absolute RT criterion). The ANOVA for RT based on the absolute RT criterion including a negative and a positive threshold (+/-10°/s) yielded a main effect for the factor validity ($F(2,22) = 31.18$, $p < 0.01$, $\eta_p^2 = 0.74$). Validly primed trials (*M* = 285 ms, *SD* = 43 ms) led to shorter RTs than invalidly primed ones (*M* = 330 ms, *SD* = 26 ms, $p < 0.01$) and neutrally primed ones (*M* = 320 ms, *SD* = 35 ms, $p < 0.01$). Thus, the validity effect observed for the relative RT criterion was not replicated with the absolute RT criterion, which accounts for a possible first RT in the wrong direction. Relative to the number of all given trials in each condition of validity, the negative cutoff for the determination of RT was excessed by 22.5% of all validly primed trials, by 38.5% of all neutrally primed trials and by 24.6% of all invalidly primed trials.

The ANOVA based on the absolute RT criterion including only the positive threshold (+10°/s) also yielded a validity effect ($F(2,22) = 25.67$, $p < 0.01$, $\eta_p^2 = 0.70$) that was quite comparable with the validity effect found for the relative RT threshold.. Validly primed trials (*M* = 291 ms, *SD* = 49 ms) led to shorter RTs than neutrally primed trials (*M* = 331 ms, *SD* = 46 ms, $p < 0.01$). The latter ones were shorter than RTs in invalidly primed trials (*M* = 353 ms, *SD* = 24 ms, $p < 0.05$).

2.6.4 Discussion

As expected, a RT validity effect (based on the relative as well as on the absolute RT criterion including only a positive threshold) was observed in a lane change task in which responses were prepared by valid, neutral or invalid primes. However, the pattern of error rates did not correspond well to the RT results. The kinematic analysis yielded a complex picture of phase modifications that tended to illustrate advantages for the valid condition compared with the neutral and invalid conditions.

Reaction times. Referring to the relative RT criterion, primes led to RTs about 41 ms shorter in the valid than in the neutral prime condition. In turn, RTs in neutral trials were about 22 ms shorter than in invalid trials. With the steering wheel velocity profile of invalidly primed trials in mind, the longer RTs for invalid trials have to be further explained. The RT calculation is based on a relative criterion: it is derived from the positive 10% threshold of the the initial steering submovement's PV. This definition implies a steering movement into the correct lane change direction and does not account for any wrong initial reactions. Therefore, RT in all trials is not derived from a possibly erroneous first incorrect steering movement but rather from the subsequent corrective (and also correct) movement. Otherwise one might conclude from visual inspection of Figure 25 that RTs in invalid trials might even be comparable with valid or neutral trials, although the movement direction is wrong. Also, one might argue that reactions in invalidly primed trials are additionally penalized by the relative RT criterion since PV in these trials was higher than in valid or neutral trials. Consequently, the relative 10%-threshold might be reached later in time for invalid trials, so that an absolute RT criterion could be supposed to be more adequate in this context. These arguments were further confirmed by an additional RT analysis based on an absolute threshold (+/-10°/s) that did not show any differences between neutrally primed and invalidly primed trials. Even this result might be counterintuitive, since one could expect that reactions resulting from false preparation might be as fast as reactions resulting from correct preparation. A possible explanation for this slowing consists in the assumption that participants already recognized their false preparation during the initial moments of the steering wheel movement and thus, although they could not stop it anymore, might have decelerated their movement speed. Consequently, the RT criterion was reached a bit later (i.e. about 45 ms) than in valid trials. From a methodological perspective, RT based only on the positive threshold might reflect a "double" RT, since it does not consider a possible first erroneous reaction. Thus, it could be considered confounded. However, RT based on the positive or negative threshold accounts for a potentially wrong initial reaction and thus reflects the "true" RT.

But which RT is relevant for the purposes of this thesis? To find an answer to this question, a first fundamental difference between this experiment and response priming experiments in basic research has to be stressed again. RT in this experiment is derived from a continuous measure, i.e., the steering wheel trajectory, whereas in basic research it is often derived from discrete events, such as keypresses. From a behavioural perspective, with discrete reactions it appears to be easier to draw the line between correct and incorrect reactions, since pressing the false key typically leads to the exclusion of the trial. It is also clear for the participant to see the difference between a correct and an incorrect response, since pressing the wrong key is an explicit false reaction. With a continuous measure the definition of an incorrect reaction is much more a matter of defining an adequate threshold that seems to be reasonable to the investigator. However, the participant is not necessarily aware of an incorrect response, unless he receives explicit feedback. Thus, in an experiment with discrete reactions, a covert corrective action preceding an overt correct response might only become visible in measures such as the LRP or the EMG (see e.g. Miller, Coles, & Chakraborty, 1996). Still, such a corrective action would lead to a prolongation of RT in case of a subsequent correct response. With regard to the steering wheel movement, one could argue that the corrective action becomes visible in the movement trajectory. It therefore nicely illustrates the online inhibition and stopping of the prepared response and the reprogramming of the unexpected response. These processes are supposed to underlie false preparation (Larish & Frekany, 1985; Lépine et al., 1989; Leuthold, 2003). Also from an applied perspective, RT based only on the positive threshold can be regarded as adequate. This RT is ecologically valid since it illustrates perfectly what might happen in case of false preparation due to a potential system failure: Free of doubt, RT for the correct response would increase. In such a scenario, the first RT of a “double” RT can be considered irrelevant, since it would not help to remedy the situation. For these reasons, it seems justified to stick to the positive threshold in the following discussion. As was shown by the additional calculations based on an absolute positive criterion (+10°/s), the RT validity effect occurred in both cases. Thus, invalid trials having a higher PV than valid and neutral ones were not penalized to an extent that might have distorted the results. As a result, the following discussion continues to focus on the RTs and kinematic measures derived from the positive relative RT threshold (10% of the PV).

The analysis of validly and neutrally primed trials is comparable with the analysis of event-specifically and temporally cued trials in Experiment 3. Interestingly, the absolute RT difference between these conditions sank from 70 ms in Experiment 3 to only 41 ms in the current experiment. Thus, the absolute advantage of response preparation in terms of milliseconds was reduced by approximately 40%. Presumably, this reduction was caused by the awareness of the participants that the prime might be invalid in a certain percentage of all trials. Consequently, response preparation was not induced to the same extent as in Experiment 3, where the precue was always valid. The absolute RT difference is somewhat smaller than in basic response priming experiments: Leuthold (2003, Experiment 1, high preparation group) reported a 56 ms advantage for valid versus neutral (41 ms in the current experiment) and a 96 ms advantage for valid versus invalid primes (63 ms in the current experiment). Although the proportion between valid (75%) and invalid trials (25%) was comparable, Leuthold deployed less neutral trials (20% of all trials) than in this experiment (50% of all trials). Larish and Frekany (1985, Experiment 2) reported RT advantages ranging between 116 ms and 164 ms for valid trials (75%) versus invalid (25%) trials, however, these authors did not present any neutral trials to their participants. Thus, the size of the absolute RT difference might be influenced by two factors. First, the lane change task is a continuous driving task that requires permanent monitoring and steering, i.e., low-level control processes. These processes might absorb cognitive resources that lead to a reduction of the validity effect. Second, half of all trials in this experiment were neutral trials, whereas Leuthold (2003) deployed 20% neutral trials, Larish and Frekany (1985) even abstained completely from neutral trials. The large amount of neutral trials might have reduced the participant's willingness and motivation to make intensive use of the directional primes, thereby lowering the effects of response preparation.

Nevertheless, the occurrence of reliable RT differences between valid, neutral and invalid trials shows that the participants were able to use and benefit from the primes. But, as was hypothesized, response preparation also produced costs in the case of false preparation. In real life, a vehicle travelling at 100 km/h covers approximately 2 m in 69 ms. This distance seems to be quite short and possibly meaningless. However, in terms of braking or swerving distance it could mean the difference between impact and no impact. Moreover, the validity effect was observed under highly controlled conditions and all participants were well aware of the fact that the preparatory prime could be invalid. In a real scenario, the percentage of critical valid ADAS information is expected to be much higher, possibly higher than 99%. In the rare case of false response preparation due to a false ADAS alarm, the driver might need a much longer RT in order to despecify and reprogram an adequate motor response, since he would not expect the ADAS to deliver false information. The additional time required to correct the response can be suspected to reduce time to collision or time headway. If the validity effect holds for such an applied scenario such as driving, one might infer that no (or only temporal) preparation could be more effective than wrong preparation, as neutrally primed reactions require less RT than invalidly primed reactions. Consequently, ADAS based warning algorithms might consider this RT difference in critical situations when the risk of wrong system information is given.

Although the response priming paradigm is a powerful technique to study response preparation, its ecological validity has been put into question by Sterr (2006). This author argued that in everyday life actions are performed under anticipated and unanticipated conditions, requiring a flexible movement execution. For this reason, Sterr implemented a no-response condition that was primed correctly in 80% and incorrectly in 20% of the trials. The latter condition represented the unanticipated movement execution since participants were required to react although they did not expect to do so. Apart from the expected validity effects, the author observed longer RTs in invalid no-response trials than in invalid go-trials. This effect was interpreted as evidence for no pre-activation of the motor system in the invalid no-response condition. For further research in driving, this variation of the response priming paradigm might be helpful, as it covers a typical driving situation in which a typically reliable ADAS misses a relevant or even dangerous traffic situation (e.g., due to technical failure of the system). The risk associated with technical unreliability might be estimated with this paradigm.

Error rates. Since anticipations occurred almost exclusively in valid trials, one might argue that participants did not wait until they could perceive the imperative signal clearly and therefore turned into the primed direction too early. If this was true, than a corresponding error rate of lane changes into the wrong direction would have been expected for invalid trials. As this was not the case, one might argue that participants waited until they completely perceived the imperative signal and were able to correct the prepared steering movement. If this is true then anticipatory reactions with RTs shorter than 150 ms would be very unlikely to occur at all. Thus, it is difficult to explain the higher percentage of anticipations in valid trials than in invalid and neutral trials.

Kinematic variables. It was hypothesized that valid primes would enable the participants to execute the steering response more efficiently. As in Experiment 1, efficiency was understood as a shortening of the two kinematic phases centered around the first peak steering wheel angle, given that the movement quality remained comparable. As can be concluded from the kinematic analysis, the initial steering submovement (TTP1 and TAP1) and the beginning of the second steering submovement (TTP2) were executed faster when trials were primed validly than when they were primed neutrally. With regard to the comparison between valid and invalid trials, TTP1 was only speeded up for valid trials whereas TAP1 only tended to be executed faster in valid than in invalid trials. The difference between valid and invalid trials for TTP2 was not statistically significant, although the descriptive difference was quite large. This picture seems to reflect three aspects of response execution prepared by response priming. First, the valid prime was not only supportive in preparing the response (as indicated by RT) but it also enabled the participants to efficiently execute the response. Since the qualitative checks did not reveal any disadvantages for validly primed steering movements, the interpretation in terms of increased efficiency seems to be admissible. Secondly, the introduction of the invalid condition seemed to preactivate response execution. This preactivation was reflected by the initial steering movement into the wrong direction and by higher standard deviations for this condition. For this reason, the disadvantage might have been not as statistically apparent for invalid trials as for neutral trials, at least with regard to the length of the different movement phases. The quality of invalid trials, expressed by the number of corrective movements, was worse than in neutral trials. This could be seen as another argument for the corrective character of the steering movement in the invalid condition. However, the inspection of the mean lateral deviation did not reveal any differences between validly and invalidly primed trials. Astonishingly, only lane changes to the right were compromised by neutrally primed trials, which is difficult to explain. Lane changes to the right were consistently performed worse throughout most of the experiments, as if they were more difficult to steer than lane changes to the left, at least for right-handed participants. This interpretation might justify the assumption that lane changes to the right were more vulnerable to the effects of response priming than those to the left.

The enhancement of the movement integration-hypothesis (Adam et al., 2000) receives some additional support by the current data. It seems that response preparation positively affects not only information processing but also response execution in sequential reversal movements, especially in later movement phases. As was found in the first experiment for trials with full event-specific preparation, TTP1 was shortened in valid trials compared with neutral and invalid trials. As already mentioned, this effect has also been observed for simple aiming movements (Mieschke et al., 2001). Given that not only ballistic but also controlled movement phases benefit from response preparation, one might conclude that the controlled part of a movement is steered by preprogramming as well as by online programming.

Conclusion. The RT analysis based on the relative as well as on the positive absolute RT criterion yielded a RT validity effect in the lane change task indicating fastest reactions in the valid and slowest reactions in the invalid condition, with the neutral condition lying in between. The kinematic analysis revealed advantages for the valid over the neutral condition with regard to movement efficiency, whereas the invalid condition was possibly compromised by its corrective character. In general and like Experiment 1 and 3, response preparation was found again to have beneficial effects on both RT and response execution.

2.7 Experiment 6: The Influence of HUD Stereoscopic Depth on Information Processing

Experiment 6 and 7 were designed in order to adapt the basic experimental paradigms of event-specific and temporal preparation to an applied problem, i.e., the design aspects of HUDs. The general idea of these two experiments is that an advantageous HUD design should lead to benefits in temporal and event-specific response preparation compared with a disadvantageous design. The spatial depth of HUDs, i.e., a variable that (among other things) serves to realize so-called “conformal symbology” (Tufano, 1997), was chosen as a design parameter to be investigated.

2.7.1 Introduction

The preceding five experiments have shown that event-specific and temporal advance information presented in an HUD influence driving performance in a lane change task. RT advantages as well as more efficient steering movements were observed in lane changes with full advance information compared with lane changes with partial or no advance information. The optimal duration of the preparatory FP ranged between 600 and 1200 ms. These experiments support the assumption that evidence about temporal (Müller-Gethmann et al., 2003; Niemi & Näätänen, 1981) as well as about event-specific (Requin et al., 1991; Rosenbaum, 1980) advance information might be generalized to a lane change task.

Apart from the optimal duration of the preparatory FP and the optimal amount of advance information, additional aspects of information presentation in HUDs seem to be relevant for successful HUD deployment in vehicles. Some of these aspects to be considered consist in for example size, colour, position and illumination of the HUD information (Ward & Parkes, 1994). In addition, HUDs have the advantage of presenting “conformal symbology” (Tufano, 1997). The term “conformal” was introduced by Naish (1964). It describes any element that can be seen as a virtual analogon to elements in the distance. Conformal HUD symbology can better be realized in aircrafts than in vehicles, as it requires equal optical distances of environmental and HUD information, so that eye accommodation and vergence movements are avoided. For a pilot, most of the surrounding objects can be considered to be in optical infinity, whereas a vehicle driver always moves through a changing environment offering various visual cues at different distances.

Contrary to assumptions about the benefits of HUDs, certain risks come along with HUD implementation. The U.S. Department of Transportation warns against the so-called “cognitive tunnelling” or “cognitive capture” (Gish & Staplin, 1995; Jarmasz, Herdman, & Johannsdottir, 2005). Tasks that produce a high perceptual load bear the potential of attracting the observer’s attention to such an extent that a perceptual narrowing, and consequently a loss of attention for surrounding objects, is the result (Ward & Parkes, 1994). Wickens and Long (1995) found evidence for this effect in simulated landing approaches. They let the participating pilots fly simulated landing approaches and varied the display's position (HUD vs. HDD) and the type of information presentation (conformal vs. non-conformal). The authors could show that visual scanning due to the HDD increased the deviation from the optimal landing track by 30% compared with the HUD. In addition, the conformal display supported the pilots’ performance better than the non-conformal display, so that the combination of an HUD with a conformal display seemed to be the optimal solution for this flight task. But the conformal HUD induced a cognitive tunnelling effect: the pilots did not react adequately to an aircraft crossing the runway in front of them; they even failed to notice it. Additional evidence for enhanced cognitive tunnelling by conformal displays was delivered by Ververs and Wickens (1998). Explicit shifts in visual attention induced by HDDs that require eye movements, changes in accommodation and vergence seem to reduce the negative effects of cognitive tunnelling (Ward & Parkes, 1994). With regard to the automotive sector, it is unclear to what extent conformal symbology in HUDs supports cognitive tunnelling. Another potential disadvantage of HUDs relies in the limited display surface of HUDs. When different pieces of information are displayed in spatial proximity additional attentional resources are absorbed. A classical example for this effect is the “flanker effect” (Eriksen & Eriksen, 1974): In the flankers task, subjects have to react to a target letter that is accompanied by two irrelevant letters (the flankers) presented to the left and right of the target. Compatible trials are made up of a target and flankers that require the same response; on incompatible trials the flankers require the opposite response as does the target. The flanker effect consists in the result that compatible trials produce faster and more accurate responses than incompatible trials.

HUD elements might also cover and hide objects in the environment, an effect termed “visual clutter”. The more elements are displayed, the larger the potential visual clutter will be (Martin-Emerson & Wickens, 1997). As a consequence, the advantages and disadvantages of HUD deployment lead to a trade-off between clutter and scanning. On the one hand, there are additional costs produced by covert information; on the other hand, the processing of information from different sources is supported (Yeh, Wickens, & Seagull, 1999).

Technically, conformal symbology can be achieved by synchronous movement of the information with the environment (Jarmasz et al., 2005), a symbology integrated into the environment (McCann & Foyle, 1995) or spatial depth of the information (Kaiser, 2004). In aviation, perceptual and cognitive effects of HUDs on pilot performance have already been studied for some years (Crawford & Neal, 2006; Fadden, Ververs, & Wickens, 1998). Also the spatial depth of information presentation in conformal HUDs has been considered, especially in the form of 3D pathway displays (Fadden, Ververs, & Wickens, 2001). The increasing deployment of HUDs in vehicles asks to what extent spatial depth of conformal HUD information is advantageous for cognitive processing compared with 2D and 2½D displays. Although conformal versus non-conformal vehicle HUDs (e.g. Caird, Horrey, & Edwards, 2001) as well as planar versus perspective HUDs have been experimentally compared (e.g. Williams & Green, 1993), the spatial depth of information has not been investigated as single dependent variable so far. Instead, luminance, contrast, display resolution, symbol size, colour (Ward & Parkes, 1994), background complexity (Ward, Parkes, & Crone, 1995) or HUD position (Yoo, Tsimhoni, Watanabe, Green, & Shah, 1999) were analyzed. Tam and Stelmach (1998) found that stereoscopically produced spatial depth could already be detected correctly of almost half of their participants at a display duration of only 20 ms. With increasing display duration, the percentage of participants who correctly discriminated spatial depth increased to almost 100% at a display duration of 1,000 ms. As this time period for depth discrimination can be considered very short, spatial depth of information might affect the speed of cognitive information processing. According to that, RTs to analogous stimuli that differ only with regard to the spatial depth dimension should vary only with regard to this dimension. Consequently, in Experiment 6 the design variable to be analysed was the spatial depth of HUD information. The experiment was designed to evaluate the influence of a directional arrow's spatial depth on information processing in a lane change. Experiment 7 should then answer the question as to what extent the spatial depth of a directional arrow might affect response preparation in a lane change.

The spatial dimensions to be compared consisted in a 2D, a 2½D and a 3D representation of the same directional arrow. Given that the representation of a complex 2D arrow in the other two dimensions necessarily leads to different arrow outlines, an additional 2D arrow with a very simple contour was introduced in order not to penalize the 2D condition for its complex form. It was expected that the 3D representation of the directional arrow would lead to an RT advantage compared with the other spatial representations. As the 3D representation perfectly fits into the environment, perceptual processes of detection and identification should be facilitated. Thus, the presumably advantageous 3D form should shorten the time required for information processing. As the spatial depth was suspected to cause only slight RT differences in an applied driving task, the vehicle's locomotion along the spatial depth axis was varied in this experiment between constant speed and no speed at all. Due to the missing vehicle dynamics in the longitudinal direction, RTs were expected to be shorter in this condition than in the constant speed condition (Lappe, Bremmer, & van den Berg, 1999).

2.7.2 Method

Participants. Twelve subjects participated in this experiment, half of them female. The average age was 23.00 years (*SD* = 2.05 years, range 19 to 26 years). The mean yearly driving experience was 6,042 km/year (*SD* = 7,066 km/year). All participants, except one left-handed person, were right-handed and had normal or corrected-to-normal vision. Colour vision and stereoscopic vision were found to be normal in all participants. All participants discriminated successfully stereoscopic images up to 60 arc seconds.

Driving task, apparatus and stimuli. The experimental task was realized with the help of the lane change task described in the preceding experiments. As already mentioned, the locomotion of the simulated vehicle was varied in two levels. In one condition, the vehicle moved with constant speed as in the preceding experiments. In the second condition, the vehicle did not move forward along the longitudinal axis; it only shifted its position along the lateral axis according to the steering wheel movements. Both conditions required exactly the same motor reaction, i.e., the complete steering wheel movement for a lane change. Changes of orientation were comparable between both conditions.

All stimuli were presented in the same location as in the preceding experiments. In each trial, a temporal precue and an imperative stimulus were presented. A two-dimensional red star (23 cd/m^2) with a diameter of 2.3° of visual angle served as temporal precue. The following imperative stimulus was realized as a green directional arrow (74 cd/m^2) that indicated the direction of the required lane change (see Figure 26). This latter stimulus was varied threefold in spatial depth. In the 2D version, it was presented in a simple (breadth × height: 9°×2.9° of visual angle) as well as in a complex form (3.9°×7.5° of visual angle). The perspectively distorted 2½D version of the arrow (11.8°×1.9° of visual angle) was created from the outline of the complex 2D arrow that was tilted by 90° toward the direction of travel. Eventually, a 3D version of the arrow (11.8°×1.9° of visual angle) was also created from the same tilted 2D arrow. This last stimulus used a stereoscopically created spatial depth and was considered the conformal arrow. All arrow versions covered a surface of equal size on the screen.

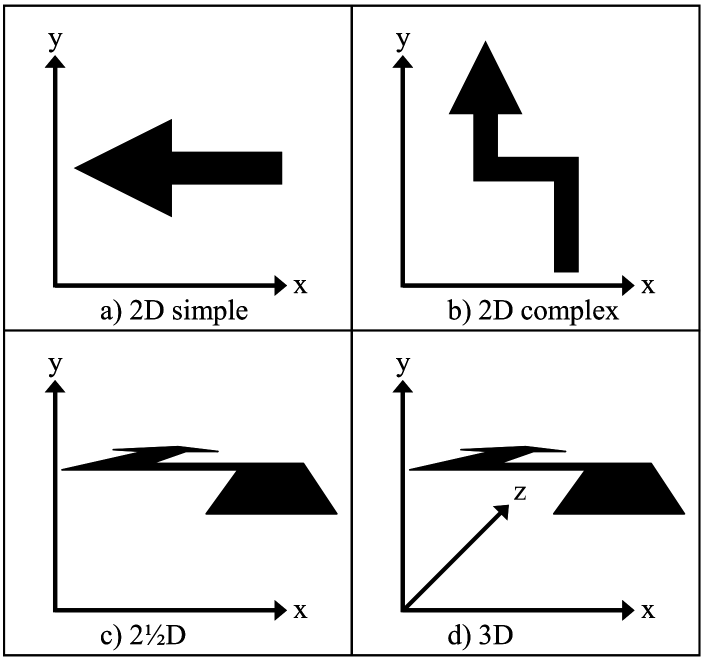

Figure 26: Schematic description of the directional arrows in Experiment 6. a) simple 2D arrow; b) complex 2D arrow; c) 2½D arrow, corresponds to arrow b), but perspectively tilted by 90° in the longitudinal axis z; d) 3D arrow with additional spatial depth. All arrows covered the same surface on the screen.

Procedure. After the general introduction given in all experiments, the driving task was explained and the participants were told the meaning of the precues and the imperative stimuli. They were not told how many different versions of the imperative stimuli existed. In order to get used to the fixed-base simulator the participants were given the opportunity to try the driving task and the steering of the simulated vehicle until it was obviously clear to the investigator that the task was understood. Participants were instructed to keep the vehicle best possible in the middle of the road. They should use the temporal precue in each trial to prepare themselves optimally to the upcoming imperative stimulus. They were asked to respond as quickly as possible but also as accurately as possible to the imperative stimulus with a lane change into the required direction.

Each experimental session lasted about two hours. It consisted of 18 blocks, each of them having 48 trials. A blocked presentation, balanced over all participants, was chosen for the locomotion condition. Consequently, the first 9 experimental blocks were either the constant speed or the no speed conditions; blocks 10 to 18 presented the other condition accordingly. The first block of each locomotion condition (i.e. the blocks 1 and 10) was considered training and discarded from data analysis. Within each block, each experimental condition (Dimension of HUD × Lane Change Direction) was presented 8 times in random order. Mean RT and its relative change to the preceding block were computed for each block and given as feedback at the end of each block. The participants were instructed to use the feedback break for a short recovery and to start the next block on their own.

Each trial started with an initial interval of 800 ms + X ms, with X being an exponentially distributed random variable with a mean of 1 s (see Figure 27). After this interval, the precue was presented for 300 ms. A FP with a duration of 1200 ms separated the precue from the imperative stimulus that was also presented for 300 ms. The participants were given additional 3500 ms to execute the lane change after the imperative stimulus. In the case of anticipatory reactions (RT < 100 ms), lane changes into the wrong direction, lane changes of more than one lane and misses (reactions being too slow, RT > 1,000 ms), the participants received respective error messages.

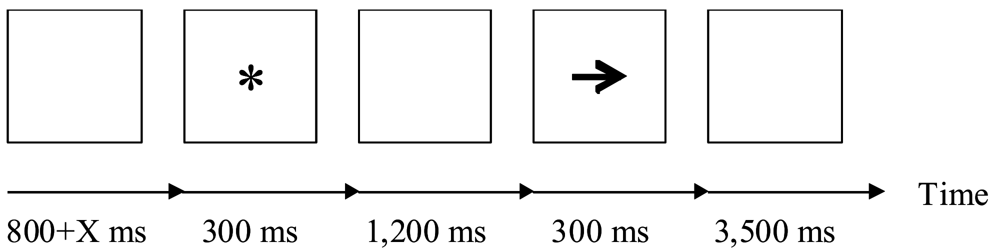

Figure 27: Basic scheme of an experimental trial in Experiment 6. The quadratic frame represents the HUD projection surface. X is an exponentially distributed random variable with a mean of 1s. In this example the 2D arrow is presented.

Experimental design. The experimental design was a complete 2×4×2 within-subjects design. Three factors were combined in this experiment: locomotion (constant speed vs. no speed), dimension of the HUD (2D-simple, 2D-complex, 2½D, 3D) and lane change direction (left vs. right). The main dependent variables were RT and error rates.

Data reduction and data analysis. The data was processed as described in the general section.

2.7.3 Results

Error rates. The overall percentage of trials with errors was 1.74%. These trials were discarded from data analysis. In 0.86% of all trials, participants changed more than one lane. There were 0.50% premature responses (anticipations). 0.16% of all responses were too slow (misses). In 0.10% of all trials the participants reacted before the appearance of the imperative stimulus, and in 0.10% they changed into the wrong direction. The experimental factors did not exert any influence on these error rates.

Reaction times. A 2×4×2 (Locomotion × Dimension of HUD × Direction of lane change) univariate ANOVA with mean RT as dependent variable was conducted (see Figure 28). The ANOVA revealed a main effect of the factor locomotion ($F(1,11) = 13.82$, $p < 0.01$, $\eta_p^2 = 0.56$). The direction of this main effect corresponded to the prediction: The no speed condition ($M = 316$ ms, $SD = 27$ ms) led to shorter RTs than the constant speed condition ($M = 331$ ms, $SD = 32$ ms). Furthermore, an interaction between the factors locomotion and dimension of HUD was detected ($F(3,33) = 3.03$, $p < 0.05$, $\eta_p^2 = 0.22$). Pairwise comparisons with Bonferroni-correction for multiple testing did not find any difference between the four HUD dimensions in the constant speed condition. However, in the no speed condition the complex 2D arrow ($M = 322$ ms, $SD = 28$ ms) was processed slower ($p < 0.05$ and $p < 0.01$, respectively) than the 2½D arrow ($M = 314$ ms, $SD = 27$ ms) and the 3D arrow ($M = 312$ ms, $SD = 29$ ms). In addition, the interaction between the dimension of the HUD and direction of lane change was significant ($F(3,33) = 4.58$, $p < 0.01$, $\eta_p^2 = 0.29$). To explain this effect the data was collapsed across the factor locomotion. Three Bonferroni-corrected t-tests for dependent samples showed that lane changes to the right initiated by the complex 2D display ($M = 327$ ms, $SD = 31$ ms) were executed slower ($p < 0.05$) than those initiated by the 2½D display ($M = 320$ ms, $SD = 33$ ms) and the 3D display ($M = 319$ ms, $SD = 33$ ms).

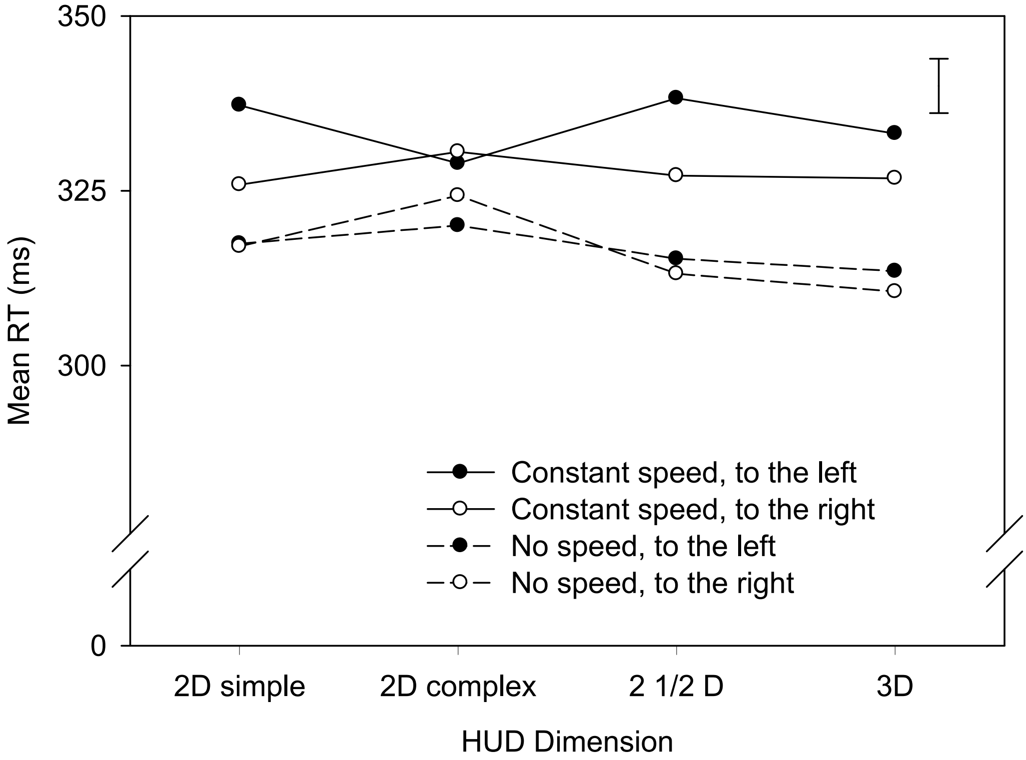

Figure 28: Results of Experiment 6 for different HUD dimensions. Mean RT as a function of locomotion, direction of lane change and dimension of the HUD. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

2.7.4 Discussion

The HUD's spatial depth was identified as one factor determining conformal symbology (Kaiser, 2004). Since a 3D HUD display was assumed to fit better into the environment, RT advantages were expected in a lane change task for 3D HUD symbology compared with 2D and 2½D HUD symbology. Such a finding would support the idea of increased information processing facilitation by conformal HUD symbology compared with non-conformal HUD symbology.

The results of this experiment did not confirm the hypothesis, as no differences between different HUD dimensions were found in the constant speed condition. However, a two-way interaction between the factors locomotion and dimension of HUD was revealed. This interaction was the result of a RT disadvantage for the complex 2D directional arrow compared with the 2½D and the 3D arrow in the no speed condition. The explanation for this RT disadvantage could reside in the orientation of the axis of sight that is directed further upwards when driving forward compared with standing still. When driving the heading of the vehicle is generally controlled by a far point of orientation, being situated some meters in front of the vehicle (Salvucci & Gray, 2004). In contrast, in the no speed condition (or even at low speed) the lateral position of the vehicle on the road can be controlled by a near point of orientation, and a far point is not necessarily required (Land & Lee, 1994). In Experiment 6, the shape of the complex 2D directional arrow partly covered the surface above the horizon, whereas the other arrows were situated lower on the screen. Due to its spatial position on the screen, the complex 2D arrow probably induced eye movements upwards in the no speed condition. Since these eye movements are not necessary in the driving condition, they may have resulted in increased RTs.

The finding of a general RT advantage for the no speed condition suggests hat the cognitive efforts in the no speed condition were lower than in the constant speed condition. This is plausible since the driving condition required additional efforts for processing the self-motion in driving direction (Lappe et al., 1999). An unexpected finding of this experiment consisted in a RT shortening for lane changes to the right in the 2½D and the 3D condition compared with the complex 2D condition. Evidence concerning such directional effects seems to be quite inconsistent (e.g. Wallis et al., 2002), so that any concept of explanation (e.g. by handedness or the road side one usually drives on) remains speculative.

Based on these results, the presumed advantages of the HUD's spatial depth on information processing were not confirmed. However, a practical hint resulting from the two-way interaction between locomotion and HUD dimension for applied investigations can be inferred. Due to the differential effects of the HUD dimension in a constant and a no speed condition, the evaluation of HUD design parameters should take place while driving. Otherwise, the experimental results might be confounded due to the potentially lowered axis of sight when standing still.

2.8 Experiment 7: Preparatory Effects of Stereoscopic Depth on Steering Performance

Experiment 7 was conducted to see whether the spatial depth of a directional arrow exerts an effect on the response preparation processes for a lane change. As was shown in Experiment 1, response preparation for a lane change is supported by partial and especially by full advance information about direction and number of lanes to be changed. Based on theses results, the movement precuing paradigm (Requin et al., 1991; Rosenbaum, 1980) was adapted in Experiment 7 to assess whether conformal display symbology supports parameter specification for a lane change motor program.

2.8.1 Introduction

According to the ideas of Anson, Hyland, Kötter and Wickens (2000), the characteristics of the precue influence response preparation as well as the number of precued response parameters. Compared with a conformal display, the non-conformal display induces less compatible stimulus-response conditions and thus increases the efforts for cognitive transformations to prepare the response. For this reason, an environmentally integrated directional 3D arrow (compared with a 2D and a 2½D arrow) should have a positive effect on response preparation. Another line of argumentation for an advantage of a conformal HUD compared with a non-conformal one can be derived from the ideomotor principle described in section 1.1.1 (Greenwald, 1970; Hommel, 1996; Prinz, 1987, 1990). This principle states that a voluntary action can be elicited by the thought of the intended effect. As Elsner and Hommel state (2001), "actions are controlled by anticipating their effects". Consequently, the better the effect can be imagined, the easier the motor system can fire off the appropriate motor program. It seems likely that the directional arrow's conformal 3D shape makes it easier to build up the action effect's internal representation. It simply illustrates the lane change trajectory in a more realistic way than any other shape.

In fact, for the execution of a lane change into the required direction, the driver only has to extract the directional information from the arrow. Consequently, if he is given enough time to prepare the driving maneuver, the dimension of the HUD does not matter at all. Therefore, an advantage for a conformal arrow representation can only be expected for a short preparatory temporal interval. In a blocked FP paradigm, short FPs lead to shorter RTs

(Niemi & Näätänen, 1981) since the estimation of the duration of long FPs is more difficult (Klemmer, 1956). According to this argumentation, in Experiment 7 a positive effect of a 3D directional arrow compared with a 2D and a 2½D arrow shape on the response preparation of a lane change was expected only when temporal preparation was well supported.

Since positive effects of response preparation were mainly found in the preceding experiments for event-specific preparation but not for temporal preparation, this experiment was designed to replicate the event-specific pattern of kinematic results. If a conformal display supports response preparation more effectively than a non-conformal display one might expect a more efficient integration of the movement phases themselves. In this sense and according to the movement integration-hypothesis (Adam et al., 2000), this integration should be revealed by shorter kinematic movement phases around the first maximum steering wheel angle (van Donkelaar & Franks, 1991a).

2.8.2 Method

Participants. Overall 14 participants took part in Experiment 7. Three participants had to be excluded from the experiment. One of them did not pass the TNO, another one showed almost exclusively anticipatory responses. The third one was excluded due to technical problems with the fixed-base simulator. Consequently, the data of 11 participants was considered for data analysis, of whom 7 were female and 4 were male. The mean age of the sample was 24.45 years (*SD* = 3.30 years, range = 18 to 30 years). The mean driving experience per participant totaled 10,455 km/year (*SD* = 13,560 km/year). All participants had normal or corrected-to-normal vision and were all right-handed, except one left-handed subject. Colour vision was found to be normal in all participants and stereoscopically produced depth could be discriminated up to 60 arc seconds.

Driving task, apparatus and stimuli. Apparatus and stimuli were similar to those employed in Experiment 6. However, the representations of the precue and the imperative stimulus were changed. The precue consisted either of the simple 2d arrow, the 2½D arrow or the 3D arrow. These arrows were employed as imperative stimuli in Experiment 6. The precue was displayed in red. It also served as a temporal warning signal since two different FPs (300 ms, 1200 ms) were employed. The precue always announced the direction of the upcoming lane change correctly and was hence 100% valid. The imperative stimulus was a simple horizontal 2D arrow with a shaft length of 4.3° of visual angle, a shaft breadth of 0.4°

of visual angle and an arrowhead, of which the basis extended to 2.5° of visual angle and of which the top had an extension of 0.4° of visual angle.

Procedure. The procedure in Experiment 7 was almost identical to that of Experiment 6. The participants were instructed to prepare the upcoming lane change as well as possible based on the information presented by the precue. They were told that the directional prediction of the precue was always valid. Although there was only a single constant speed condition in this experiment, the entire experimental session lasted about 2 hours. This was due to the introduction of the temporal FP that was presented in a blocked fashion and balanced over all participants. So the first half of the experiment consisted either of trials with a short FP (300 ms) or with a long FP (1200 ms). In the second half, the other FP duration was presented accordingly. In each session, 18 blocks of 48 trials each were run. Each remaining condition (Dimension of HUD × Direction of Lane Change) was presented eight times in each block in random order. Block 1 and 10 were considered as training blocks and were discarded from data analysis. Apart from the FP duration, the temporal scheme of a trial corresponded to that of Experiment 6 (see Figure 27).

Experimental design. The experiment factorially combined FP duration (300 ms vs. 1,200 ms), dimension of HUD (2D, 2½D or 3D) and direction of lane change (left vs. right) in a complete within-subjects 2×3×2 design. The main dependent variables were RT, error rates, the kinematic variables TTP1, TAP1, TTP2 and TAP2 and the qualitative variables.

Data reduction and data analysis. The data was processed as described in the general section. Three-way univariate repeated measures ANOVAs with the factors FP duration, dimension of HUD and direction of lane change were performed for error rates, RT, the kinematic and quality variables.

2.8.3 Results

Error rates. Overall 26.09% of all trials had to be eliminated from data analysis due to errors. This percentage of errors was made up primarily of anticipations that summed up to 21.07% of all trials. 2.18% of all trials were discarded because the participants reacted before the appearance of the imperative stimulus. In 1.97% of all trials, the participants changed more than one lane; in 0.73% of all trials, they reacted too slowly. Lane changes into the wrong direction occurred in 0.11% of all trials. Eventually 0.03% of all trials were not considered as the participants left the track completely.

Since anticipatory errors occurred in a considerable number of trials, mean anticipatory error rates were submitted to an ANOVA. It revealed main effects for the factors FP duration ($F(1,10) = 41.68$, $p < 0.01$, $\eta_p^2 = 0.81$) and HUD dimension ($F(2,20) = 10.70$, $p < 0.01$, $\eta_p^2 = 0.52$). Anticipatory errors were committed almost exclusively in the short FP condition (short FP: $M = 1.30\%$, $SD = 0.60\%$, vs. long FP: $M = 0.10\%$, $SD = 0.00\%$). Pairwise post-hoc Bonferroni-corrected comparisons showed that mean anticipatory error rates in the 2D display condition ($M = 0.80\%$, $SD = 0.33\%$) were higher ($p < 0.05$) than in the 2½D display condition ($M = 0.60\%$, $SD = 0.33\%$) and in the 3D display condition ($M = 0.70\%$, $SD = 0.33\%$). A two-way interaction between the factors FP duration and lane change direction ($F(1,10) = 9.95$, $p < 0.01$, $\eta_p^2 = 0.50$) revealed that the difference between error rates for lane changes to the left and those to the right was larger in the short FP than in the long FP.

Reaction times. The ANOVA of mean RTs (see Figure 29) revealed main effects for each factor. With regard to FP duration ($F(1,10) = 45.05$, $p < 0.01$, $\eta_p^2 = 0.82$) mean RTs were shorter in the short FP ($M = 232$ ms, $SD = 53$ ms) than in the long FP condition ($M = 320$ ms, $SD = 65$ ms). The main effect for the dimension of HUD ($F(2,20) = 3.82$, $p < 0.05$, $\eta_p^2 = 0.28$) was the result of a tendency ($p < 0.1$) to shorter RTs in the 2D condition ($M = 272$ ms, $SD = 60$ ms) than in the 3D condition ($M = 279$ ms, $SD = 51$ ms), as could be revealed by Bonferroni-corrected pairwise comparisons. Eventually, shorter RTs ($F(1,10) = 8.12$, $p < 0.05$, $\eta_p^2 = 0.45$) were observed for lane changes to the right ($M = 271$ ms, $SD = 51$ ms) than for lane changes to the left ($M = 281$ ms, $SD = 59$ ms).

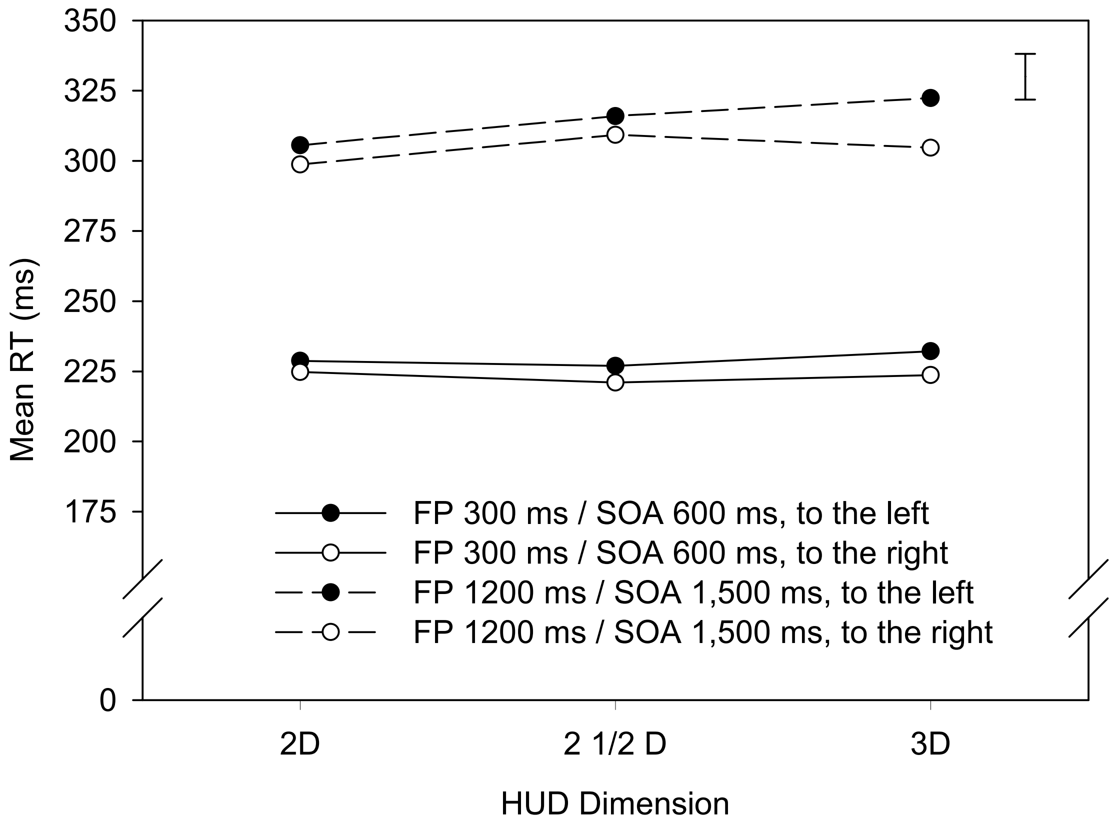

Figure 29: Results of Experiment 7 for temporal and adapted event-specific preparation. Mean RT as a function of FP/SOA duration, direction of lane change and dimension of HUD. The standard error was computed according to Loftus (2002).

Kinematic variables.

Steering wheel angle trajectory. The steering wheel trajectory clearly illustrates an earlier movement onset for the short than for the long FP (Figure 30). However, the visual inspection does not deliver any hint about consistent trajectory shape differences with regard to the distinct HUDs. Compared with the preceding experiments, the maximum steering wheel angle is smaller than observed in Experiment 2, Experiment 3 and Experiment 5. At the same time, the minimum steering wheel angle seems to be higher than in the preceding experiments.

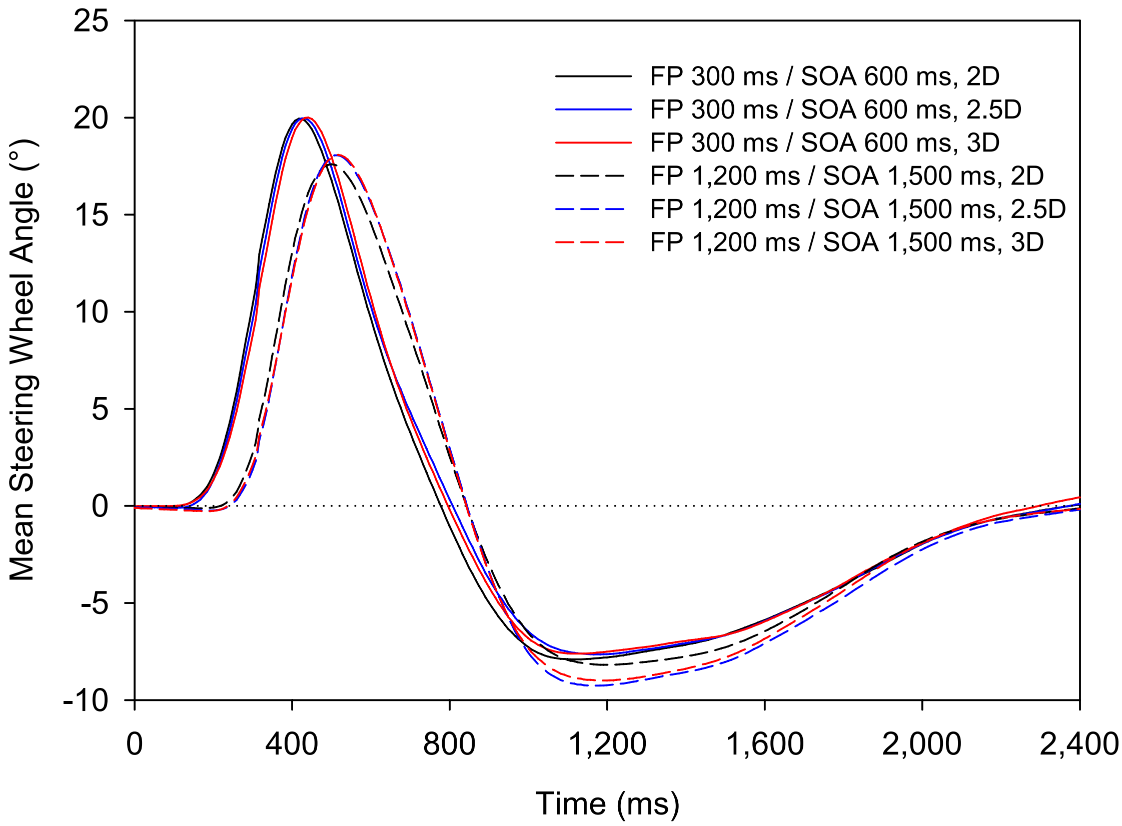

Figure 30: Results of Experiment 7 for the steering wheel angle trajectory. Mean steering wheel angle (collapsed across lane change direction) as a function of FP/SOA duration and HUD dimension. Onset of the imperative stimulus at Time = 0 ms.

Steering wheel velocity. As was observed for the trajectory, the peaks of the steering wheel velocity seem to be dampened compared with the preceding experiments. The graphical illustration (Figure 31) depicts the potential difference in movement onset between the short and the long FP, whereas the HUDs do not evoke visually recognizable differences between the experimental conditions. After the steering wheel minimum has been reached, it seems as if the movement was corrected more intensively in the short FP condition.

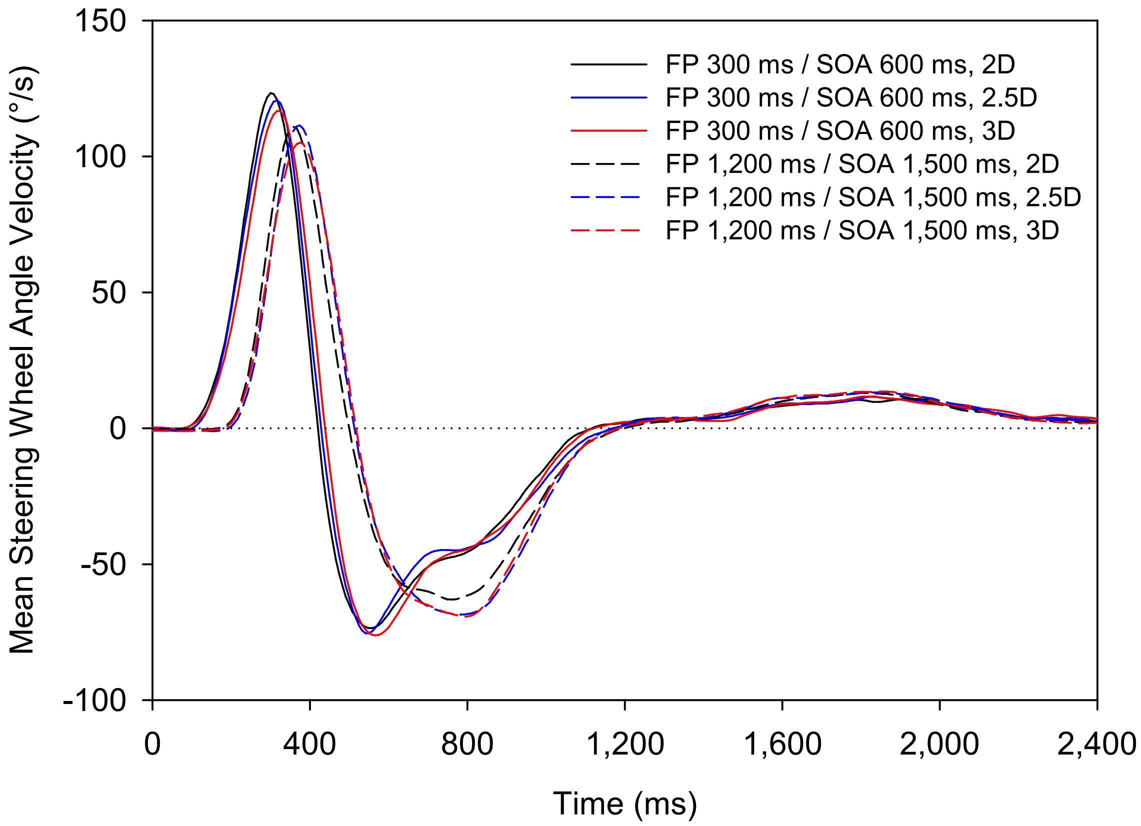

Figure 31: Results of Experiment 7 for the steering wheel angle velocity profile. Mean steering wheel angle velocity (collapsed across lane change direction) as a function of FP duration and HUD dimension. Onset of the imperative stimulus at Time = 0 ms.

Initial steering wheel submovement

Time to peak steering wheel velocity (TTP1). The factor direction had a main effect on TTP1 ($F(1,10) = 7{,}69$, $p < 0.05$, $\eta_p^2 = 0.44$). Lane changes to the left exhibited shorter TTPs (M = 135 ms, SD = 30 ms) than those to the right (M = 142 ms, SD = 29 ms).

Time after peak steering wheel velocity (TAP1). Experimental factors had no effect on TAP1.

Second steering wheel submovement

Time to peak steering wheel velocity (TTP2). The factor dimension of HUD affected TTP2 ($F(2,20) = 3.76$, $p < 0.05$, $\eta_p^2 = 0.27$) insofar as TTP2 tended to be shorter ($p = 0.11$) for the 2D-display (M = 326 ms, SD = 113 ms) than for the 3D-display (M = 334 ms, SD = 116 ms). Additionally, the ANOVA yielded a trend to shorter TTPs ($F(1,10) = 3.43$,

$p < 0.1$, $\eta_p^2 = 0.26$) for lane changes to the left (*M* = 322 ms, *SD* = 117 ms) than to the right (*M* = 337 ms, *SD* = 115 ms).

Time after peak steering wheel velocity (TAP2). TAP2 was not affected by any experimental factor.

Quality checks

Corrective movements. The ANOVA did not reveal any effect of the experimental factors on the number of corrective movements.

Lateral deviation. The only significant effect on the mean lateral deviation was exerted by the factor direction ($F(1,10) = 7.08$, $p < 0.05$, $\eta_p^2 = 0.42$). The participants came closer to the target when changing to the left (*M* = 19.46, *SD* = 2.81) than to the right (*M* = 17.99, *SD* = 2.27).

2.8.4 Discussion

Reaction times and error rates. The findings replicate evidence from basic research: Short FPs in a blocked FP paradigm lead to shorter RTs than long FPs (Niemi & Näätänen, 1981). In addition, shorter mean RTs were observed when participants reacted to the 2D HUD than when they reacted to the 3D HUD. The hypothesis that an environmentally highly compatible 3D arrow would facilitate the processes of action preparation in a lane change task was not confirmed. A simple 2D arrow proved to be more effective. The analysis of anticipation error rates can also be interpreted this way. Anticipations were almost exclusively observed when temporal preparation was good, i.e., in the short FP condition. The tendency to react too early can therefore be explained by a better timing of the motor reaction, since the length of the short time interval can be estimated more reliably than the length of the long time interval (Klemmer, 1956). Moreover, more anticipatory reactions emerged in the 2D HUD than in other HUD conditions. This fact might be understood as a faster cognitive processing of the simple arrow form.

Which reasons might be responsible for the missing influence of spatial depth on action preparation in this lane change task? First, the 2D arrow shape used in this experiment might belong to the class of overlearned stimuli. Although symbolic endogenous cues such as centrally presented arrows have to be decoded before their spatial meaning is determined

(Jonides, 1981; Müller & Rabbitt, 1989), such overlearned stimuli may be processed involuntarily and almost automatically, potentially facilitating preparatory processes (Hommel, Pratt, Colzato, & Godijn, 2001; Pratt & Hommel, 2003). With regard to HUD design recommendations, this interpretation would lend support for a simple symbol language that allows a maximum of automatic processing, thus rendering the cognitive efforts for understanding the meaning of any symbol as low as possible.

Contrary to the expectation derived from the ideomotor principle (Greenwald, 1970; Hommel, 1996; Prinz, 1987, 1990), 3D spatial depth did not facilitate the completion of the lane change task. One trivial reason for this failure might be that the employed 3D arrow simply did not correspond to the "response image" stored internally. Consequently, it did not support the initiation of the required action. Another potential reason regarding the "missing" anticipation of the action's effect might consist in the assumption that the expected advantages of a 3D arrow did not compensate for the effect of an overlearned stimulus. In fact, the spatial depth was not a prerequisite for the successful completion of the task, since only the directional information had to be extracted from the stimulus. Thus, the processing of the arrow shape was sufficient to fulfil the task; bottom-up-processing of the stimulus did not necessarily require the extraction of spatial depth. Although depth perception can be qualified as a low-level process, it is not necessarily free from top-down influences. Especially in stereoscopic projections it can be assumed that 3D-objects might be recognized based on their 2D-traces rather than based on their 3D-structure (Bülthoff, Bülthoff, & Sinha, 1998). In order to remedy this effect in another experimental setup, a task requiring correct discrimination of spatial depth for task completion or at least for task facilitation would be required. The investigation of visual collision avoidance systems or distance warning systems may represent a promising alternative.

Tam and Stelmach (1998) suppose that discrimination of stereoscopic depth requires a long temporal integration period. This process may require more time than other visual functions. For this reason, it remains open whether a stimulus duration of 300 ms was sufficient for the process of depth discrimination.

The perception of a stimulus' spatial depth is also influenced by the forms of surrounding elements (Kumar & Glaser, 1992). Trapezoidal forms, in particular, tend to support the perception of depth insofar as the perspective implies that the smaller side of the trapezoid is farther away in depth. In this experiment, the road markings that separated the lanes from each other formed an alignment that resembled the slanted lines of a trapezoid. It cannot be excluded that the perspective on the road markings changed the perception of the 2D and 2½D arrows, so that the arrow top was always perceived farther away than the arrow base. If this was the case, the 3D arrow did not offer any additional advantage.

Kinematic variables. It was expected that the conformal display would allow a more effective integration of the movement phases located around the first steering wheel angle. However, the analysis of the kinematic parameters of the steering wheel movement did not support this hypothesis. The current results did not show any advantages for the 3D HUD, and were hence in line with the RT results. Contrary to expectation, TTP2 was shorter in the 2D condition than in the 3D condition. This advantage might be the result of the shorter RT for this condition, indicating a more effective response preparation for the simple than for the complex HUD. Nevertheless, this advantage did not affect TAP1 and thus is qualitatively different from the preparatory effects observed in Experiment 1 and 3. In addition, lane change direction influenced the ballistic movement phases. Lane changes to the left exhibited shorter ballistic movement phases than lane changes to the right, thus confirming the observations made in some of the preceding experiments.

Conclusion. The results of this experiment did not go along with the hypotheses. The conformal display did not lead to more effective response preparation, neither with regard to RT nor with regard to kinematic movement properties. The extent to which overlearned simple stimuli or the experimental operationalization of spatial depth could account for the results in this experiment was discussed.

3 General discussion

This chapter is divided into three sections. In the beginning, the major findings of this thesis as well as their accompanying interpretations are summarized. Then, the general limitations concerning all experiments are mentioned and commented. Finally, a number of future directions for the present line of research are discussed.

3.1 Summary of Findings and Interpretations

Driving a vehicle is a highly complex task, involving a variety of dynamic subtasks. Consequently, understanding the cognitive processes in driving is a challenging task (Salvucci, 2006). It can be assumed that drivers prepare their responses according to the available sources of information in order to fulfil the driving task more efficiently. Seen from this point of view, driving requires a permanent and constant programming and reprogramming of the motor system. Any information reducing uncertainty about what to do at which point in time might render this motor programming more efficient (cf. Requin et al., 1991). The driver's preparation for action is supported by e.g. traffic signs, dashboard instruments, additional IVIS and ADAS (pertaining to vehicle status and the environment).

With regard to RT patterns, this study examined the extent to which the well-studied mechanisms of temporal preparation (Niemi & Näätänen, 1981) and event-specific preparation (Requin et al., 1991) apply to driving situations with regard to movement precuing (Rosenbaum, 1980) and response priming (Larish & Frekany, 1985; Rosenbaum & Kornblum, 1982). In addition, the study analyzed potential kinematic effects of action preparation in lane change steering movements. Since in all experiments basic experimental paradigms were combined with a driving task, the study was something between basic research and applied research. The three paradigms of action preparation were implemented into a newly developed lane change task. It was attempted to replicate and enhance respective findings from basic research in a first series of five experiments. Then, in Experiment 6 and 7, the experimental approaches of temporal and event-specific preparation were adapted and slightly modified to study the preparatory effects initiated by three-dimensional HUDs. In the following summary, the first five experiments will be described according to the respective experimental paradigm that was under investigation. Next, the last two experiments will be summed up together. All results will be summarized in Table 7.

3.1.1 Movement Precuing

The first experiment served to investigate the effects of event-specific response preparation in the lane change task by implementing a movement precuing paradigm (Rosenbaum, 1980, 1983). A typical precuing effect for RTs was expected. At the same time, it was hypothesized that evidence for the movement integration-hypothesis (Adam et al., 2000) could be found by detecting symmetrical shortenings in the steering wheel velocity profile around the first peak steering wheel angle (van Donkelaar & Franks, 1991a). The RT results were in line with the results of previous research, since RTs became shorter when precue information was given, especially when both information about number of lanes and lane change direction were presented (see e.g. Anson et al., 2000; Leuthold et al., 1996; Spijkers & Steyvers, 1984). The appearance of this precuing effect was interpreted as an indicator of analogous preparatory processes in unimanual discrete and bimanual reciprocal, point-symmetrical movements of complex steering tasks. According to the movement integration-hypothesis, the kinematic pattern of results argued for a functional dependence between the first and the second steering submovement. The kinematic precuing effect observed in this experiment seemed to underpin the view of van Donkelaar and Franks (1991a), who assume that most planning efforts concentrate on the first turning point of a reversal movement. The current kinematic results were only partly in line with the two-component model of limb-control (Beggs & Howarth, 1970; Carlton, 1981; Chua & Elliott, 1993, 1997), which posits preparatory effects only for the first and ballistic part of a movement. In a next step, the experimental focus switched from event-specific preparation to temporal preparation.

3.1.2 Temporal Preparation

The second experiment was conducted in order to examine the effects of temporal preparation (Niemi & Näätänen, 1981) in the lane change task. Lane changes were expected to be initiated earlier with temporal preparation than without temporal preparation. Moreover, mean RTs were assumed to follow a U-shaped function with RT being minimal for a medium FP duration. Kinematic effects were expected for the PV of the initial steering wheel movement, such that PV might be high when temporal preparation is low. No further hypotheses were formulated for the duration of the kinematic movement phases. As expected, the general effect of temporal preparation – indicated by shorter RTs in any FP condition compared with a no FP condition – was confirmed. Unexpectedly, temporal preparation was already best at the shortest FP, so that the resulting RT function only partly followed a U-shaped function indicating worst performance in the longest FP. Shortest RTs in the shortest FP of a variable FP paradigm contradicted basic evidence (Näätänen, 1970) and were explained by the effective length of the preparation period that summed up to 600 ms (precue duration plus FP duration, Los & Schut, 2008). In addition, no RT differences were found over a quite long FP range of 900 ms, contributing to the flat shape of the RT function. Since an optimal state of readiness lasting longer than 0.4 s is generally considered to be unlikely (Alegria, 1974; Gottsdanker, 1975; Näätänen, 1970), this finding spoke more for a general alleviation of RT differences between the FPs (possibly due to the participants' permanent lane-keeping efforts) than for an optimal state of readiness lasting almost 1s. Temporal preparation did not exert a systematic influence on the kinematic properties of the steering wheel movement, neither on PV nor on the duration of the kinematic movement phases. This result seemed to confirm the assumption that temporal preparation might have differential effects on RT and reaction kinematics (Fitts, 1954; Frowein & Sanders, 1978; Meulenbroek & van Galen, 1988). As described in the experimental outline of the thesis, the next experiments served to combine event-specific preparation in terms of movement precuing and temporal preparation.

3.1.3 Movement Precuing and Temporal Preparation

In Experiment 3 and 4, event-specific and temporal preparation were combined in order to study potential interactions between both processes. As in the preceding experiments, RT advantages were expected for trials with event-specific preparatory information and for trials with medium FPs. In addition, an interaction between both factors with regard to RT was hypothesized. Temporal preparation was not expected to influence the kinematic movement properties systematically. However, event-specific preparation was expected to shorten the two kinematic phases around the first peak steering wheel angle, thus replicating the findings of the Experiment 1. To start with, the main effect of event-specific preparation on RT was replicated and thus confirmed. Also, the main effect of temporal preparation was found again. The latter effect indicated best behavioural performance in terms of shortest RTs in the medium FPs. Contrary to other findings (Spijkers & Steyvers, 1984) and according to the AFM logic (Sternberg, 1969), the interaction between temporal end event-specific preparation suggests an impact of both processes on the same stage in the human information processing chain. According to the conclusions of Correa et al. (2006), it was assumed that this stage might be the motor stage, since the task was mainly focused on a fast motor steering reaction, but did not pose any perceptual difficulties. Presumedly, it required the preparation of late stages more than the preparation of early stages in the information processing chain. The interaction itself suggested that a temporal state of readiness might fade away later when event-specific preparation is higher.

With regard to the kinematic results, the main effect of event-specific preparation centered around the first peak steering wheel angle, shortening the corresponding two kinematic phases directly before and after this peak. This result was in line with the results from Experiment 1 and thereby confirmed the assumption that event-specific response preparation might be relevant not only for information processing (i.e. for faster response onsets) but also for efficient response execution. The kinematic effect of temporal preparation was very limited, since only the last phase before the first peak steering wheel angle was affected. In addition, this effect was not consistent with the results of Experiment 2. For this reason, it was concluded that temporal preparatory effects might increase the general state of readiness, but do not necessarily influence the quality of response execution.

The following experiment was intended to further analyze the interaction between temporal and event-specific preparatory processes, especially for short FPs. To this end, the design reincorporated the no FP condition that was dropped in the preceding experiment. It was expected that this condition should yield the longest RT compared with all other FPs. In addition, a FP of 0 ms was introduced which corresponded to an effective preparation period of 300 ms (SOA 300 ms, see Los & Schut, 2008), since the warning stimulus was displayed for this duration. This FP was assumed to yield longer RTs than the subsequent medium FPs. Eventually, the experiment aimed to further explore the interaction between event-specific and temporal preparation in its early phase.

In general, the main effects of temporal and event-specific preparation known from the preceding experiments were replicated. Confirming the finding of Experiment 2, temporal preparation was optimal after an effective temporal preparation period of 600 ms. Nevertheless, 300 ms of effective preparation time were not sufficient to build up optimal temporal readiness. This finding might hint at a deceleration of the temporal preparation process compared with basic laboratory experiments (see e.g. Bertelson & Tisseyre, 1968;

Müller-Gethmann et al., 2003). Event-specific preparation shortened RTs by about 50 ms, thus replicating the findings of Experiment 1 and indicating that navigational information such as direction was supposed to be highly useful in this task. Although an interaction between both processes was observed again, this interaction was clearly different from that one found in the preceding Experiment 3. The RT differences between mere temporal preparation and mere event-specific preparation were stable across all FPs except the shortest one. Thus, the conclusion drawn from Experiment 3 could not be confirmed: Contextually helpful information did not support the maintenance of a state of readiness for a longer period. Rather, the interaction illustrated the temporal assembly process of event-specific preparation. That is to say, the processing of contextual information may have required time and might not be fully accomplished after only 300 ms of effective preparation time.

Although the open issues concerning the interaction between temporal and event-specific preparation could not be resolved conclusively and thus necessitated additional empirical work, the series of experiments was continued as planned. The next topic under investigation consisted in the implementation of an additional event-specific preparation paradigm, i.e., the response priming paradigm.

3.1.4 Response Priming

The response priming paradigm (Larish & Frekany, 1985; Rosenbaum & Kornblum, 1982) was introduced as an additional instrument to investigate event-specific preparation in the current lane change task. On RT level, response priming was expected to produce a validity effect in the driving task by preparing the drivers either validly, neutrally or invalidly for an upcoming lane change. With a view to the kinematic characteristics of the lane change steering wheel movement, the experiment aimed to replicate the effect of event-specific preparation (Experiment 1), i.e., the shortening of the kinematic phases around the first turning point of the steering wheel movement. In accordance with the hypothesis, a validity effect for RT was observed that was smaller than that reported in the literature (e.g. Larish & Frekany, 1985; Leuthold, 2003). Two hypothetical explanations were put forward for the decrease in size: the high percentage of neutral primes (50% of all trials) deployed in the experiment and the continuous attention required by the driving task, limiting the cognitive resources available for response preparation. The kinematic analysis yielded advantages for the valid condition compared with the neutral condition with regard to movement efficiency, though the invalid condition might have been compromised by its corrective character. As was also observed in the first experiment, adequate response preparation shortened not only the kinematic phases around the first peak steering wheel angle but also the first ballistic phase. From this it was concluded that initial and later movement phases might benefit both from response preparation processes.

With the response priming experiment, the investigation of basic response preparation paradigms in the current lane change task came to an end. In the remaining two experiments, it was planned to make use of and adapt these response preparation paradigms to an even more applied context so as to prove their usefulness for practical questions.

3.1.5 Conformal Head-Up Display

In the concluding two experiments of this thesis, it was investigated to what extent stereoscopically produced 3D depth supports performance in a lane change task. 3D depth can be regarded as a conformal characteristic of HUDs (Kaiser, 2004). Thus, it might support cognitive information processing and response preparation more effectively than 2D or 2½D HUDs. Contrary to these assumptions, no RT-advantages for the 3D display compared with 2D and 2½D displays were observed, neither in Experiment 6 nor in Experiment 7. However, from these experiments some post-hoc inferences were drawn that might serve as hypotheses for subsequent experimental investigations. In Experiment 6, four different HUD dimensions were tested in a no speed condition and a constant speed condition, resulting in a two-way interaction between this locomotion factor and the HUD dimension. Interestingly, the interaction was based solely on a RT disadvantage of the complex 2D arrow compared with the 3D and the 2½D arrow in the no speed condition whereas there were no differences between the HUD dimensions in the constant speed condition. This result can be interpreted as a serious hint for any display design that might be implemented in moving vehicles. As the axis of sight is oriented higher with regard to the vertical axis in a moving vehicle, form and shape recognition of any display symbol may work differently than in a vehicle standing still. Thus, advantages for any symbol shape or form derived from a static experimental setup should also be shown in a dynamic setup. Experiment 7 confirmed the results of Experiment 2 and 3 in that temporal preparation acted as supportive factor for lane change performance. In addition, it suggested that simple and possibly overlearned arrow shapes (Hommel, Pratt et al., 2001; Pratt & Hommel, 2003) support response preparation more effectively than shapes with a more complex layout. An advantage for response preparation induced by a 3D HUD could not be ascertained, however.

3.1.6 Empirical Conclusion

From the experimental work of this thesis several important conclusions might be derived. It was possible to develop an experimental reductionist lane change task requiring mainly low-level control processes such as monitoring and tracking. In this task, basic processes of temporal and event-specific response preparation could be isolated. The experimental results suggest that response preparation in driving can be observed through behavioural measures, since temporal and event-specific response preparation shortened the drivers' RT. However, these behavioural measures not only incorporate RTs; they also extend to kinematic aspects of steering wheel movements, as steering wheel movement execution benefitted from event-specific response preparation, not temporal response preparation. Thus, at least two different experiments to disclose covert cognitive processing and its consequences for overt behaviour confirmed behavioural changes in the steering wheel movement due to different levels of response preparation.

More specifically, in the first five experiments basic evidence concerning the RT effects of event-specific and temporal response preparation were, for the most part, successfully replicated and enhanced in the lane change context. An additional and interesting contribution to the literature consists in the reliable changes in the steering wheel velocity profiles revealed in the kinematic analyses of the lane change steering wheel movement. These changes were interpreted as indicators of increased efficiency in response execution when event-specific parameters of the response could be prepared in advance. It is noteworthy that consistent changes in the kinematic steering wheel velocity profiles were observed even though different experimental paradigms representing event-specific preparation, i.e., movement precuing and response priming, were deployed. On the one hand, these results confirm the prevailing view of differential effects of temporal and event-specific preparation on kinematic movement properties. Temporal preparation did not consistently influence movement execution, whereas event-specific preparation did. On the other hand, and most important, these kinematic results enhance the movement integration-hypothesis (Adam et al., 2000), since they demonstrate the applicability of this hypothesis to more complex than unimanual reversal aiming movements. Of course, this observation opens a large field of additional experimental work, in basic as well as in applied research. Moreover, the findings of van Donkelaar and Franks (1991a) for unimanual reciprocal extension/flexion movements were generalized: planning efforts for bimanual, reciprocal and point-symmetrical movements seem to be invested mainly in the planning of the first turning point of the movement. In the last two experiments of this thesis, it was demonstrated that the concepts of temporal and event-specific preparation can be adapted and varied in order to investigate applied problems in HUD design, i.e., the spatial depth of conformal displays.

Concluding from the obvious ecological validity of the lane change task employed in this thesis, the experimental findings imply a generalizability of respective basic evidence to the driving context. Thus, further examination of response preparation in different applied driving situations appears possible and worthwhile. These preparatory processes, which seem to have been overlooked in applied driving research in the last decades, promise to account for specific aspects of human performance in driving. They can be seen as a model for specific aspects of driving, i.e., steering, and might contribute to further operationalize specific aspects of concepts such as situation awareness (Endsley, 1995) or cognitive tunneling (Wickens & Long, 1995). For applied research, this means that aspects of ADAS – e.g., proper timing of information, content and validity of information – can directly influence the driver's processes of action preparation. For instance, special attention could be given to the assumption that the validity effect might turn out to be even larger in real driving contexts than in simulated driving contexts. Of course, the applied examination of newly developed ADAS and IVIS focuses on these aspects, but any real-world solution might also be based on the theoretical fundament of action preparation. The successive approximation of an applied context with basic experimental paradigms, as was demonstrated in this thesis, could help practitioners develop a deeper understanding of how basic research is planned and accomplished. At the same time, basic experimental paradigms could serve him as a toolbox to analyse and evaluate applied problems. In this way, theoretically and empirically confirmed ideas about the preparation of movements can help further understand the complex challenges humans have to face when driving. This might support the mutual exchange between theoreticians and practitioners.

3.1.7 Overview of Results

Table 7 briefly summarizes the main findings. It refers to Table 1 in section 1.4.

Table 7: Summary of experimental findings.

Exp. No.	Experimental paradigm	Main research question, findings and conclusion
1	Event-specific preparation	Research question: Replication of precuing effect, analysis of kinematic properties and enhancement of basic findings. Main findings: RT precuing effect comparable with findings from basic research. A kinematic precuing effect is found for the two kinematic phases around the first turning point of the steering wheel movement. Conclusion: Evidence for the functional dependence of the first and the second steering wheel submovement according to the movement integration-hypothesis. Preparatory efforts seem concentrate on the first turning point of the movement.
2	Temporal preparation	Research question: Replication, analysis of kinematic properties and enhancement of basic findings. Main findings: Temporal preparation leads to shorter RTs. However, temporal preparation was optimal at the shortest FP. Differences between FPs were only very small. The kinematic measures were not affected consistently by temporal preparation. Conclusion: Temporal preparation is helpful on RT level. Event-specific and temporal preparation appear to have differential effects on movement execution.
3	Temporal and event-specific preparation	Research question: Investigation of a possible interaction between both (temporal and event-specific) types of preparation. Main findings: Event-specific and temporal preparation reduce RTs. Both processes interacted. The kinematic phases around the first turning point of the steering wheel movement were shortened with available event-specific information. Conclusion: Contextually helpful information seems to support the maintenance of a state of readiness. The interaction between both types of preparation suggests the same locus of effect, presumably the motor stage. Temporal preparation does not necessarily support movement execution.
4	Temporal and event-specific preparation	Research question: Further investigation of a possible interaction between both (temporal and event-specific) types of preparation. Main findings: Replication of the main effects of temporal and event-specific preparation. Both processes interacted again, but differently from the preceding experiment. Conclusion: The interaction is not in line with the findings in the preceding experiment. Rather, it seems to show that the complete processing of contextual information requires time and is built up slowly.

Continuation of Table 7: Summary of experimental findings.

Exp. No.	Experimental paradigm	Main research question, findings and conclusion
5	Response priming	Research question: Replication of validity effect and enhancement of basic findings, potential negative effects (costs) of preparation on lane change performance. Main findings: A RT validity effect was found. Valid primes shortened the kinematic phases around the first peak steering wheel angle and the first ballistic phase. Conclusion: The validity effect is robust and occurs in an applied task. Evidence for effective response preparation, i.e., the support of movement execution was strengthened.
6	Event-specific preparation	Research question: Influence of the HUD's spatial depth on cognitive processing. Main findings: No RT-advantages for the 3D display compared with 2D and 2½D displays were observed. A two-way interaction between the locomotion factor and the HUD dimension was found. Conclusion: HUD designs should be tested in dynamic environments, since a static environment might deliver deviant results.
7	Adaptation of event-specific preparation, temporal preparation	Research question: Influence of the HUD's spatial depth on event-specific preparation. Main findings: No RT-advantages for the 3D display compared with 2D and 2½D displays were observed. Temporal preparation was supportive for lane change performance. Conclusion: The results suggest that simple and possibly overlearned arrow shapes support response preparation more effectively than shapes with a more complex layout.

3.2 Limitations

The degree to which the findings illustrated in the preceding sections can be generalized is limited by some specific aspects resulting from the trade-off between ecological validity and experimental control of any experiment (Loomis et al., 1999). With regard to the task design, it was intended to develop a reductionist lane change task that allows repeatable experimental manipulation of independent variables while providing ecological validity. Of course, the task design is still a compromise between the needs of experimental control and direct applicability to real driving. However, such a design allows to examine the effects of response preparation on driving performance and to link cause and effect. Nonetheless, from an applied perspective, critical factors in the preceding experiments that reduce the external validity of the results can be found in the following aspects.

Driving speed was kept constant during the entire lane change task, since any intentional speed modification, e.g., braking or speeding up, would have introduced the additional task of longitudinal vehicle control. As the idea was to let the drivers concentrate on steering, i.e., on lateral control, this potentially confounding issue was excluded in the first approach. Perhaps surprisingly for the practitioner, the simulated environment consisted of many lanes side by side and contained no real world aspects. This manipulation of the driving scenario was necessary in order to realize randomly distributed lane change directions. As can be seen from the steering wheel velocity profiles, the steering wheel trajectories elicited in this study, especially in Experiment 1, were more similar to fast corrective steering wheel movements (Hildreth et al., 2000) than to smooth lane change maneuvers executed in daily traffic. This shape is certainly due to the instructions that asked participants to react as quickly as possible. With regard to the HUDs deployed in the simulation, the size of the field of view was quite small, whereas the HUD stimuli were quite large compared with existent HUDs offering a projection surface of approximately $5° \times 5°$ (Gish & Staplin, 1995).

One can accept the conclusions of this thesis by keeping in mind the limited generalizability of simulator studies. Driving simulators do not provide the same sensory cues to the driver as the real world does (Kemeny & Panerai, 2003). They can only aim at approximating the real case. Fixed-base simulators, in particular, suffer from a reduced representation of sensory inputs, since they are typically restricted to visual and auditory cues. However, vestibular and proprioceptive cues play an important role in vehicle steering and affect driving performance (Greenberg, Artz, & Cathey, 2003; Reymond, Kemeny, Droulez, & Berthoz, 2001). In this context, it should be mentioned that the only feedback provided to the drivers was visual. No auditory or haptic stimuli were presented although the source of feedback may have a decisive role for driver performance, especially in lane change tasks (Macuga et al., 2007). For these reasons, the use of full motion simulators might deliver more valid results also in the research field of response preparation.

3.3 Relevance of the Findings and Future Directions

The approach pursued in this thesis, i.e., the combination of basic experimental paradigms with applied realistic tasks, allows a large variety of follow-up-studies. Experimental work can be continued in basic as well as in applied research. In the following sections an arbitrary selection of possible research topics that follow-up studies might focus on is presented. These considerations complete the thesis.

3.3.1 Basic Research

As was pointed out in the discussion of several experiments, some results of the current thesis were unexpected or not compliant with corresponding evidence from basic cognitive psychological laboratory work. The most striking example concerns the interaction between temporal and event-specific preparation investigated in Experiment 3 and 4. Although an interaction between both preparatory processes was observed in both experiments, the pattern of results was not stable. Nevertheless, the interaction between temporal and event-specific preparation has been examined only rarely (Requin et al., 1991; Spijkers & Steyvers, 1984). Based on the current experiments, a systematic analysis of the common contribution of both processes to the final state of preparation might be worthwhile. Since temporal preparation as well as event-specific preparation have been frequently found to influence late stages of the human information processing chain (e.g. Leuthold et al., 1996; Sanders, 1980; Spijkers, 1990), one might select or design an experimental task that requires mainly motor performance and that does not require specific demanding perceptual performance (Correa et al., 2006). In this task, a certain discrete motor reaction, e.g., moving a lever into a certain position, could be prepared temporally and event-specifically. No additional vigilance task would be required, thus maximizing the chance of finding the hypothesized interaction.

The second interesting result of this study that offers a large potential for subsequent basic experimental laboratory studies is the kinematic pattern stemming from event-specific preparation. Both event-specific preparatory paradigms – movement precuing and response priming – led to comparable kinematic changes of the lane change steering wheel movement. TAP1 and TTP2 were reliably shortened when event-specific preparatory cues were either contextually complete or valid. In the context of this study, theses changes were interpreted as an index for increased response execution efficiency since no serious differences regarding lane change quality were observed between well and badly prepared maneuvers. As far as the author is aware, the work of van Donkelaar and Franks (1991a) is the only study that delivers comparable kinematic evidence for reciprocal aiming movements. In the light of the movement integration-hypothesis (Adam et al., 2000), the symmetric changes in adjacent kinematic phases around a movement turning point make sense. Any effects of response preparation becoming manifest during the time after first peak steering wheel velocity seem to be mirrored during the time before second peak steering wheel velocity, possibly due to a neuromuscular integration between agonistic and antagonistic forces. Seen from a basic experimental angle, the kinematic changes of complex, bimanual, reciprocal and symmetrical movements due to event-specific preparation and the corresponding inferences for the human information processing must still be investigated. For this reason, follow-up studies in the basic research laboratory might concentrate on a replication of the current results. Such basic studies could focus on simpler settings and movements than were deployed in this thesis. A possible simplification of the current task consists in the investigation of turns instead of lane changes. Steering a turn represents one reversal movement back and forth with the steering wheel, whereas the lane change steering wheel movement requires the sequence of two turns. Thus, a rotational reversal movement required for a turn more closely resembles a straight reversal aiming movement. Comparing kinematic changes from event-specific preparation in both movements might be worthwhile as well.

Additional experimental work could focus on the comparison between unimanual and bimanual rotating movements. In this thesis, it was posited that point-symmetrical movements comprising both arms and hands, such as complex steering movements in driving, might be prepared and controlled analogously to unimanual aiming movements. This hypothesis still awaits confirmation, however. A potential approach to this subject matter might consist in comparing the velocity profiles of unimanual and bimanual rotating movements, depending on the different states of response preparation.

Another conceivable approach to the kinematic analysis of steering wheel movements might deploy basically the same lane change task as in this thesis except for the longitudinal propulsion. 3D programming environments allow the easy withdraw of the vehicle's forward movement but still enable the translation of any rotational steering wheel movement into lateral displacements. Thus, lane changes could be steered “on the spot”, focusing on the steering movement itself and suppressing the required cognitive processing of driving speed. Such additional investigations of RT, error rates and velocity profiles might further support the notion of increased movement efficiency facilitated by event-specific preparation. Furthermore, additional correlational analyses between kinematic parameters of corresponding movement phases around the first turning point might help to strengthen the movement integration-hypothesis with regard to bimanual reversal movements.

3.3.2 The Influence of Response Preparation on Action Kinematics

The results of the experimental series conducted in this thesis suggest that response preparation influences the movement kinematics of the lane change steering wheel movement. This conclusion is based on the analyses of the steering wheel angle velocity profiles of the first and the second submovement of the entire lane change steering wheel movement. With regard to the movement integration-hypothesis (Adam et al., 2000), it was hypothesized that any changes in the velocity profile of the first submovement should also be reflected in the second reversal submovement. The logic behind this idea originates from the neuromuscular integration of agonistic and antagonistic muscle activity in reversal movements, which claim an overlap between the termination of the first and the initiation of the second movement. The antagonistic burst that slows down the first movement during the homing-in phase, i.e., the phase that is assumed to be controlled visually, is used (at least partially) in the same time as agonistic burst for the (more or less) ballistic phase of the reversal submovement.

A further research question in this kinematic context might consist in examining the relation between response preparation and the resulting velocity profiles more thoroughly. To better understand such effects, one might ask which parameters of the velocity profile functions will change in accordance to specific advance information presented before movement execution. For such a purpose, a model of the steering wheel angle velocity profiles needs to be developed and data needs to be fitted to this model. As a basis for such a model, the delta-lognormal model (Plamondon, 1995a, 1995b, 1998; Woch & Plamondon, 2010) can be used. The striking characteristic of this model consists in the assumption that a bidirectional movement, i.e., a bidirectional stroke, can be considered as one coherent movement unit. This assumption contrasts with other models that assume the existence of respective movement units for each single peak in the movement's velocity profile (Meyer, Abrams, Kornblum, Wright, & Smith, 1988). The movement units mentioned before can be considered as building blocks of an entire movement and are called “movement primitives” (Woch & Plamondon, 2004). According to the definition of Woch and Plamondon (Woch & Plamondon, 2004, 2010) a movement primitive is produced by the synchronous commands of a pair of agonistic and antagonistic neuromuscular systems. These systems emit two opposed velocity components Λ_1 and Λ_2 that, subtracted from each other, correspond to the velocity profile V(t) of fast movements. The form of this profile can then be described by the following delta-lognormal function ΔΛ (Woch & Plamondon, 2010):

$$V(t) = D_1\Lambda_1(t; t_0, \mu_1, \sigma_1) - D_2\Lambda_2(t; t_0, \mu_2, \sigma_2) \quad (1)$$

with

$$\Lambda_i(t; t_0, \mu_i, \sigma_i) = \frac{1}{\sigma_i\sqrt{2\pi}(t - t_0)} \exp - \left[\frac{[\ln(t - t_0) - \mu_i]^2}{2\sigma_i^2} \right] \quad (2)$$

Λ_i : lognormal function.

D_i : the amplitude of the agonist and antagonist command, respectively.

t_0 : timepoint of the synchronous emission of both commands.

μ_i : log time delay of the agonist and antagonist system, respectively.

σ_i : log response time of the agonist and antagonist system, respectively.

In analogy to the proposition of Adam et al. (2000), the delta-lognormal model accounts for the interaction between the agonist and the antagonist neuromuscular system and posits a certain type of synergy resulting from the synchronous emission of two commands. Interestingly, this model also holds for bidirectional movements having two velocity profile peaks (Woch & Plamondon, 2010).

With rapid steering wheel movements, one might assume that steering wheel movements also consist of movement primitives of neuromuscular activity that can be described with lognormal functions. One might thus achieve a description of the experimental data of the entire lane change steering wheel movement by deploying an adapted delta-lognormal function U(t). As was pointed out in section 2.1.4, the lane change steering wheel movement can be separated into three reversal submovements. In the terms of Woch and Plamondon, each single submovement could be characterized by a single velocity component, so that V(t) could be enhanced by a third velocity component $D_3\Lambda_3(t; t_3, \mu_3, \sigma_3)$. In addition, all three velocity components can be assumed to be emitted at different points in time in order to achieve more flexibility for this first approach. Thus, an adapted delta-lognormal function U(t) can be described as:

$$U(t) = D_1\Lambda_1(t; t_1, \mu_1, \sigma_1) - D_2\Lambda_2(t; t_2, \mu_2, \sigma_2) - D_3\Lambda_3(t; t_3, \mu_3, \sigma_3) \quad (3)$$

In this preceding function, three muscular commands make up the entire movement primitive: a first agonistic command into the required lane change direction, a second antagonistic command into the opposite direction and a final agonistic command reversing the steering wheel back into the central straight position. In a first approach to this model, the data of a movement precuing experiment, i.e., the condition with full advance information that was conducted analogously to Experiment 1 described in this thesis, was fitted successfully to this function. Figure 32 yields a graphical description of this fit.

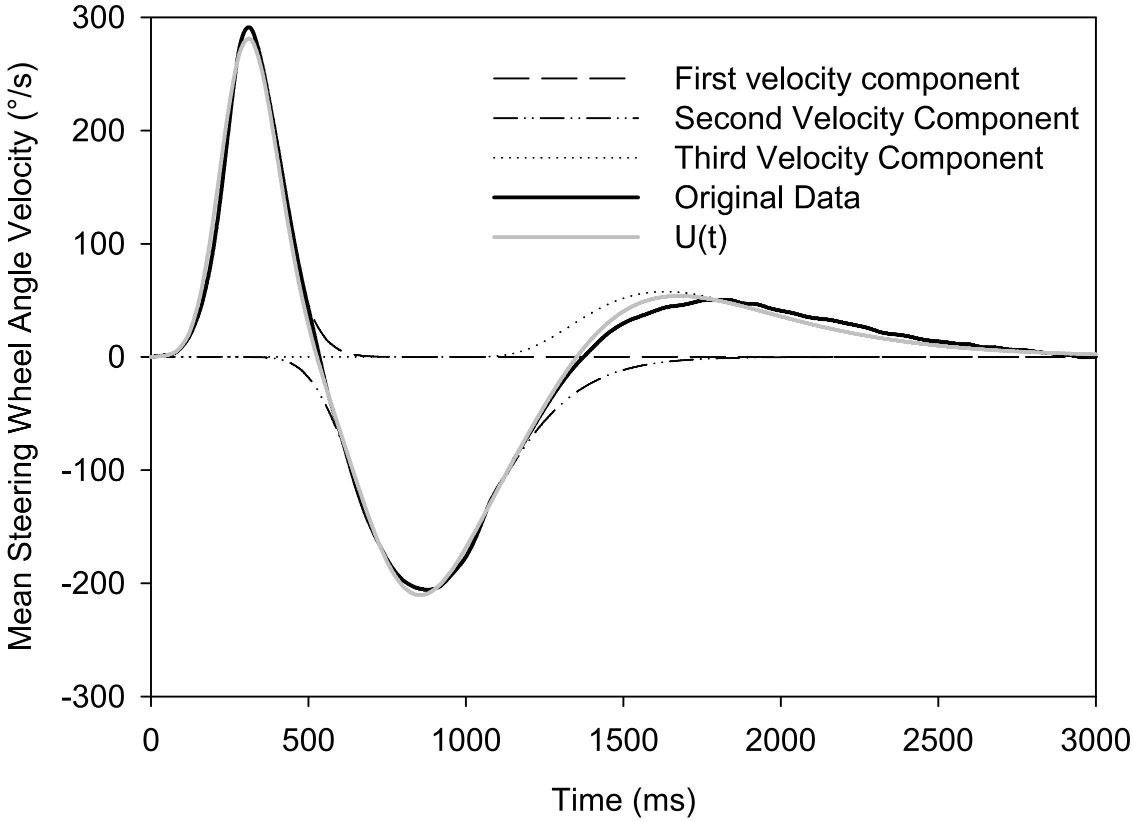

Figure 32: The adapted delta-lognormal function U(t) fitted to the steering wheel angle velocity profile. Mean steering wheel angle velocity of a full advance information condition (comparable with Experiment 1) as a function of time. Onset of the imperative stimulus at Time = 0 ms. U(t) is the additive result of the three velocity components.

Concluding from the preceding figure it seems as if the original data can be approximated accurately by the adapted delta-lognormal function U(t). The next steps in pursuing this approach consist in fitting U(t) to the remaining experimental conditions of the depicted movement precuing experiment and in submitting the fitted parameters to statistical analyses. As a potential gain from fitting the adapted delta-lognormal model to real steering wheel movements, different movement patterns in fast steering maneuvers (e.g., evasive and overtaking actions) and in smooth movements (e.g., lane changes) can be identified. Such data in turn can be used to adapt steering systems to the individual needs of drivers by considering their personal "fingerprint" for steering movements. Currently, the approach described in this section is the subject of a study on performance differences in the young and the elderly (Rinkenauer & Hofmann, in press).

3.3.3 Approaching the Real World

Seen from an applied perspective, one of the main questions resulting from this thesis is the following: What does a RT advantage of 50 to 100 ms elicited by adequate response preparation mean for real driving? Of course, this question can hardly be answered conclusively. However, an attempt to interpret such a RT advantage is justified, since any practitioner will be interested in exactly this question. As was pointed out in the introduction, RT advantages caused by event-specific and temporal preparation shorten the duration of the entire cognitive information processing chain. Early, central and late stages are supposed to benefit from these RT gains. The following interpretations should be seen against this background.

According to the "Time-Based Resource-Sharing Model" (Barrouillet, Bernardin, & Camos, 2004), processing and maintaining information in the working memory rely on the same limited resources. Moreover, cognitive steps in processing and maintenance can only take place one at a time, given a central attentional limitation. The cognitive load posed by a certain task depends directly on the proportion of time during which this task captures attention. While attention is required, concurrent activities demanding central resources are impeded. Thus, since cognitive resources are assumed to be sparse, a reduction in RT might free central resources that support memory formation and retrieval or response selection. In driving, increasing cognitive load is assumed to decrease event detection performance, to increase reaction times, to increase the gaze concentration toward the road centre, to increase steering entropy and to affect lane keeping quality, positively as well as negatively (Engström, Johansson, & Östlund, 2005). Consequently, cognitive load should be kept low in driving, and preparatory processes might help to decrease cognitive load.

With regard to the duration of cognitive steps, models of human cognition have assumed that humans possibly operate on discrete rhythmic cycles (VanRullen & Koch, 2003). The duration of such a cognitive cycle was estimated at no less than 50 ms (Meyer & Kieras, 1997), so that adequate preparation might help to process relevant information earlier. Of course, it is unclear to what extent one or two fewer cognitive steps affect subsequent overt behaviour in a real traffic scenario. But since milliseconds can be translated into meters at reasonably high speed (100 ms at 100 km/h sum up to approximately 3 m), one might come to the conclusion that every gain in RT due to adequate response preparation matters. In a real world scenario, where attentional load is much higher than in a virtual reality experiment, the RT gains by adequate response preparation can be assumed to be much higher than reported in this thesis. The reasons for this assumption are clear-cut. First, in the lane change task, participants were completely aware of what they were expected to do. So they only had to decide themselves between a limited number of steering reactions. In real life, drivers have to choose among several possible reactions such as braking, steering or speeding up in order to cope with a difficult situation. Second, orientation with regard to the traffic scenario was not necessary in the lane change task. In real traffic, the driver would have to find out from where a source of danger might approach his vehicle, identify this source and then react to it. Third, participants were highly concentrated on the lane change task, whereas in real driving scenarios, drivers are often distracted by many different influences.

Based on this comparison of driving in the laboratory and in the real world, one might derive the following experimental continuation of the current study. To start with, the deployment of a professional fixed-base driving simulator that allows a further approximation of the real case in terms of vehicle handling and environmental aspects seems to make sense. In such a driving simulator, one might investigate simple but daily driving maneuvers such as overtaking, turning at crossings or choosing the right lane at unclear intersections. These driver actions might be prepared by simple event-specific and temporal cues in order to enhance response preparation and adequate reactions. One might test the extent to which timely and adequate response preparation in advance frees cognitive capacities in the relevant driving situation itself. Possible tests consist in measuring the performance in additional tasks, e.g., visual search performance (Wilschut et al., 2008). Of course, time-critical response preparation (e.g., braking or swerving) might also be investigated further in such a scenario. As was pointed out in section 3.2, external validity might be increased even further if a full-motion simulator could be deployed for additional experimental work. A validation of the results achieved in the preceding experimental series in such a simulator could constitute the final reason for implementing experiments about response preparation. In general, such a continuation would correspond to the methodological approach of this study, namely to realize a stepwise approximation of the real case while deploying well-established paradigms of basic cognitive psychology.

3.3.4 Lane Change Task as Diagnostic Tool

It is possible to transfer and deploy the tools developed for this thesis in different contexts. The strength of the lane change task developed for the current experimental series is its high degree of standardization and experimental control, although it is clearly linked to driving. It is based on ample evidence from basic research and thus theoretically well established. This theoretical foundation in cognitive processing allows the task to be considered as a tool to assess psychomotor performance in terms of response preparation and response execution in a medical and psychotherapeutical environment.

Several studies show that depressed patients are psychomotorically retarded (Schrijvers et al., 2008; Sobin & Sackeim, 1997). Studies in clinically depressed patients reveal that a high percentage of this population is not expected to exhibit average driving performance (Brunnauer, Laux, Geiger, Soyka, & Möller, 2006). The risk of being in a traffic accidents after the prescription of antidepressants seems to be increased as well (Bramness, Skurtveit, Inke, Mørland, & Engeland, 2008). The psychomotor slowing observed in depressed patients might extend to or be based on motor programming deficits (Caligiuri & Ellwanger, 2000). In general, the ability to drive a vehicle in Germany is assessed using a test battery that focuses on visual perception, reactivity, stress tolerance, concentration and vigilance. RT and MT are typically regarded as indicators for these constructs. These test are implemented in the Vienna Test System or in the Act and React Testsystem ART-90 (see e.g. Brunnauer et al., 2008). Although these tests are standardized, they are often of the focus of criticism due to their potential lack of ecological validity (Ramaekers, 2003; Verster & Mets, 2009).

With regard to potential deficits in motor programming and execution, the lane change task presented here might serve as a basis for the development of an ecologically valid choice reaction time task in a driving context. With such a task, the diagnostic testing of certain aspects relevant for driving (e.g., motor programming ability or the speed of information processing and response execution) would be linked directly and obviously to a relevant driving maneuver. A first study linking psychomotor slowing to potential response preparation deficits in depressed patients is currently on its way (Hofmann, Rinkenauer, Golka, & Conrad, 2010). Further studies might thus examine the diagnostic capacities and the constructive validity of this lane change task by comparing drivers' performance in this task with drivers' performance in already available standardized test batteries. The final result might consist in a standardized lane change task for medical diagnostic purposes.

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List of Abbreviations

2D	Two-dimensional
2½D	Two and a half-dimensional
3D	Three-dimensional
α	Alpha; specified significance level
ADAS	Advanced driver assistance system
AFM	Additive factor method
ANOVA	Analysis of variance
cm	Centimetre
CNS	Central nervous system
η_p^2	Eta squared; measure od effect size
EEG	Electroencephalogram
EMG	Electromyogram
F	Fisher's *F* ratio
FP	Foreperiod
HDD	Head-down display
HUD	Head-up display
Hz	Hertz
ISI	Interstimulus interval
IVIS	In-vehicle information systems
LCT	Lane change task by Mattes (2003)
LRP	Lateralized readiness potential
m	Meter
ms	Millisecond
MT	Movement time
OTA	One-target advantage
p	probability
PV	Peak steering wheel velocity
r	Pearson product-moment correlation
RT	Reaction time
s	Second

SAT	Speed-accuracy-tradeoff
SD	Standard deviation
SOA	Stimulus onset asynchrony
t	Computed value of t-test
VR	Virtual reality
WTK	WorldToolKit
x	Horizontal axis in the WTK geometrical system
y	Vertical axis in the WTK geometrical system
z	Longitudinal axis in the WTK geometrical system

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Appendix A: Alternative and Additional Calculations

Appendix A presents the results of three different additional calculations:

1) The results of alternative RT calculations for Experiment 1 and 2 are described. These calculations were based on an absolute RT criterion.
2) Resulting from the alternative RT calculation TTP1 was recalculated for Experiment 1 and 2.
3) For Experiment 1, the results of correlations between RT and peak steering wheel angle as well as between RT and PV of the first steering wheel submovement are presented.

Reaction times. In these calculations an absolute RT criterion based on steering wheel angle velocity was defined and set to 10°/s. Since the definition of the RT criterion also affects the duration of TTP1, the analysis was also executed for this dependent variable.

Reaction times for Experiment 1. The analysis revealed main effects for the factors direction precue ($F(1,9) = 119.24$, $p < 0.01$, $\eta_p^2 = 0.93$) and number of lanes precue ($F(1,9) = 35.47$, $p < 0.01$, $\eta_p^2 = 0.80$) (see Figure 33). Participants responded faster with advance knowledge about lane change direction ($M = 290$ ms, $SD = 55$ ms) than without it ($M = 364$ ms, $SD = 60$ ms). This pattern was also found for advance knowledge about the number of lanes ($M = 308$ ms, $SD = 52$ ms vs. $M = 345$ ms, $SD = 62$ ms). Contrary to the relative RT criterion, the main effect for the number of lanes was not replicated.

A significant two-way-interaction between the two precue factors was observed ($F(1,9) = 11.48$, $p < 0.01$, $\eta_p^2 = 0.56$), too. Participants produced especially short RTs when both information were given in advance. As reported for Experiment 1, this finding was confirmed by a two-tailed paired t-test ($t(9) = 3.34$, $p < 0.01$) on the differences of lane changes with respectively without number of lanes precue. The t-test showed that this difference was much larger when the direction precue was given ($M = 48$ ms, $SD = 26$ ms) than the respective difference without direction precue ($M = 26$ ms, $SD = 17$ ms). However, the two-way interaction only tended to be attenuated by a three-way interaction between the two precue factors and the factor number of lanes ($F(1,9) = 4.4$, $p < 0.1$, $\eta_p^2 = 0.33$).

An additional three-way interaction was found between the two precue factors and the factor direction ($F(1,9) = 7.93$, $p < 0.5$, $\eta_p^2 = 0.47$). A two-way repeated measures ANOVA with the two precue factors for lane changes to the left revealed the interaction ($F(1,9) = 24.08$, $p < 0.01$, $\eta_p^2 = 0.73$) between the two precue factors. By contrast, the corresponding interaction failed to reach significance for lane changes to the right ($F(1,9) = 2.49$, $p = 0.15$, $\eta_p^2 = 0.22$). Thus the advantage of full advance information was larger for lane changes to the left than for lane changes to the right.

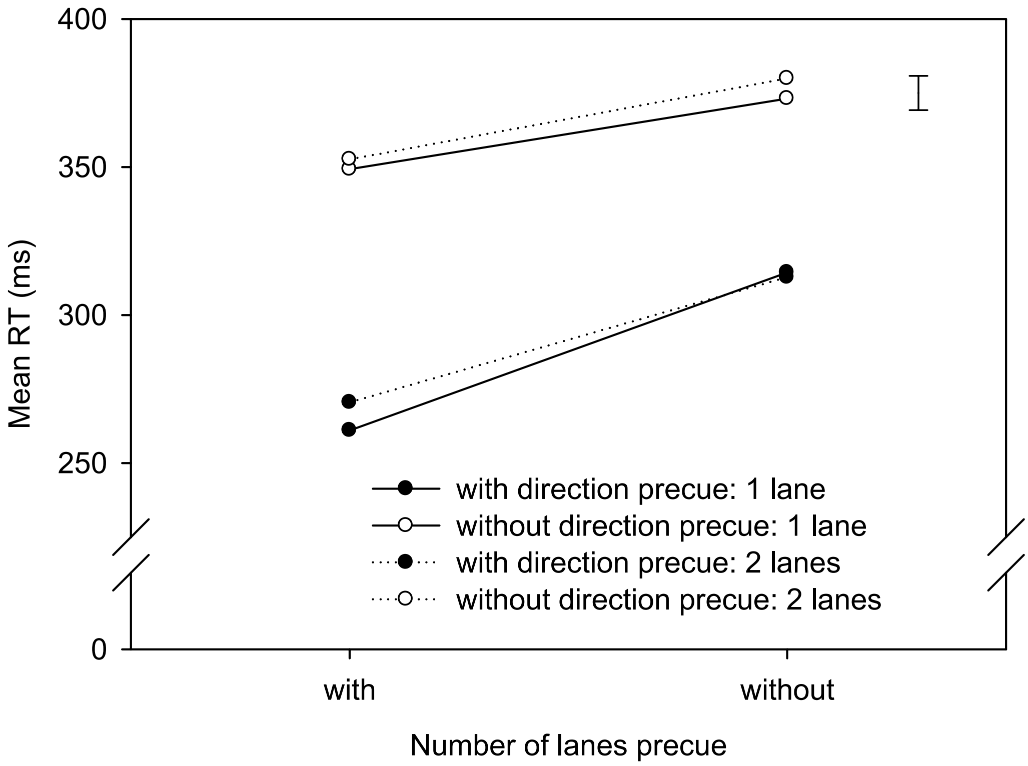


Figure 33: Results of Experiment 1 for event-specific preparation, calculated with an absolute RT criterion. Mean reaction time (RT) as a function of number of lanes, direction precue availability and lane precue availability. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

Time to peak steering wheel velocity (TTP1) for Experiment 1. As one could expect TTP1 was shorter ($F(1,9) = 44.42$, $p < 0.01$, $\eta_p^2 = 0.83$) for changes by one ($M = 140$ ms, $SD = 15$ ms) than by two lanes ($M = 157$ ms, $SD = 19$ ms). The number of lanes precue tended to yield shorter TTP1s ($F(1,9) = 5.05$, $p = 0.05$, $\eta_p^2 = 0.36$) when advance information was given ($M = 146$ ms, $SD = 16$ ms) than when it was not ($M = 150$ ms, $SD = 18$ ms). The interaction between the precue factors was more pronounced than it was reported for the relative RT criterion and tended to reach significance ($F(1,9) = 4.66$, $p < 0.1$, $\eta_p^2 = 0.34$).

Reaction times for Experiment 2. The main effect of FP was replicated ($F(1.86,20.44) = 98.83$, $p < 0.01$, $\eta_p^2 = 0.90$). Pairwise comparisons with Bonferroni-correction for multiple testing demonstrated that mean RTs in trials without temporal precue were longer (M = 425 ms, SD = 46 ms) than in trials with temporal precues, regardless of FP (FP 300 ms: M = 354 ms, SD = 32 ms, $p < 0.01$; FP 600 ms: M = 355 ms, SD = 34 ms, $p < 0.01$; FP 1,200 ms: M = 361 ms, SD = 34 ms, $p < 0.01$; FP 2,400 ms: M = 371 ms, SD = 37 ms, $p < 0.01$). In addition, the RTs in the FPs 300 ms ($p < 0.05$), 600 ms ($p < 0.01$) and 1,200 ms ($p < 0.01$) were shorter than in the longest FP of 2,400 ms. In addition to these results and contrary to the results reported for Experiment 2, mean RTs in the 1,200 ms FP were significantly longer than in the 600 ms FP ($p < 0.05$). The ANOVA also revealed an interaction between direction and FP ($F(2.93,32.21) = 2{,}72$, $p < 0.05$, $\eta_p^2 = 0.20$).

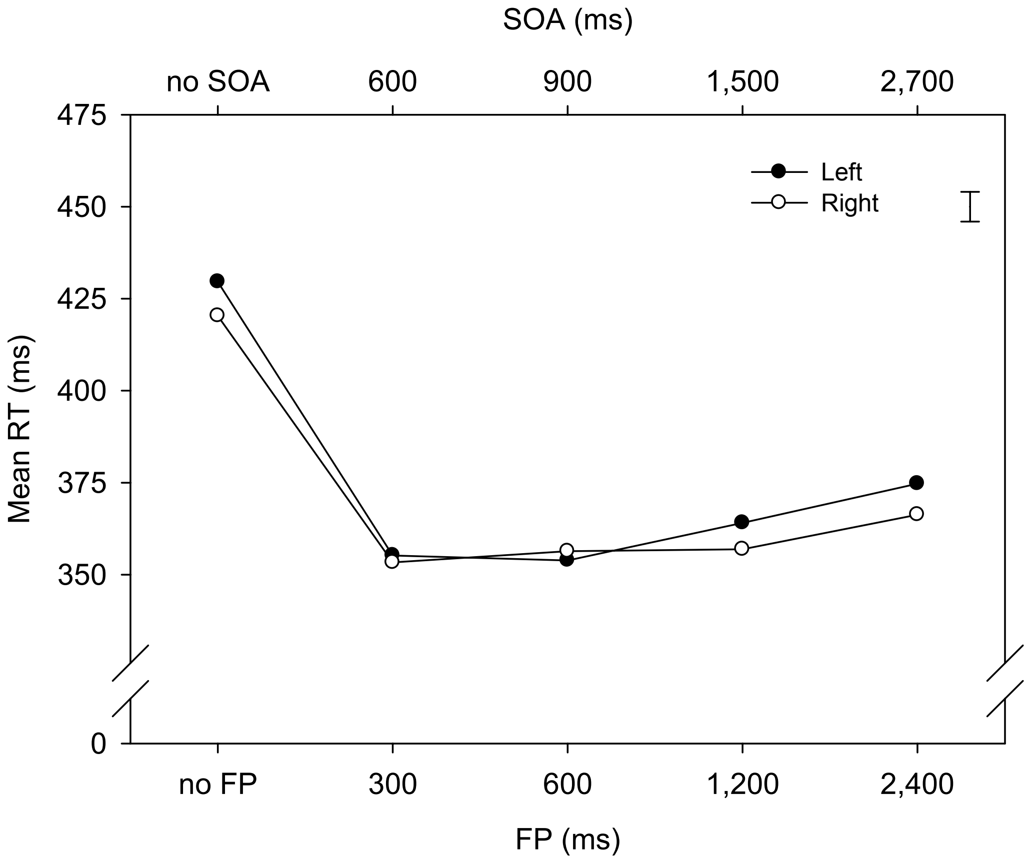


Figure 34: Results of Experiment 2 for temporal preparation, calculated with an absolute RT criterion. Mean reaction time (RT, in milliseconds) as a function of FP/SOA and direction of lane change. The standard error was computed from the pooled error terms of the corresponding ANOVA (Loftus, 2002).

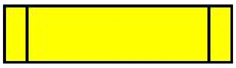
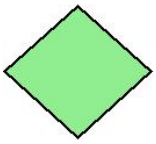
Time to peak steering wheel velocity (TTP1). TTP1 was affected neither by FP duration nor by direction. However, the interaction between both factors tended to be significant ($F(2.22,104.85) = 2.77$, $p < 0.1$, $\eta_p^2 = 0.20$).

Correlational analysis for Experiment 1. For each subject and factorial combination of Experiment 1, the correlations between RT and peak steering wheel angle as well as between RT and PV were determined. Then, ANOVAs were carried out on the Fisher's-*z*-transformed correlation coefficients. The ANOVA for the correlations between RT and peak steering wheel angle delivered a significant main effect for the direction precue factor ($F(1,9) = 7.20$, $p < 0.05$, $\eta_p^2 = 0.44$). The average correlation totalled $r = -0.06$ without direction precue and rose to $r = -0.22$ (retransformed values) with direction precue. There were no more significant effects. The ANOVA for the correlations between RT and PV yielded no significant results.

Appendix B: General Program Flowcharts

In this appendix B the simulation program structure is described by high-level flowcharts in order to supply a general overview of the system.

Table 8: Legend of symbols used in the program flowcharts.

	Start or end of a program block.
	Block of procedures.
	Input/output.
	If-then decision.
	Procedure.

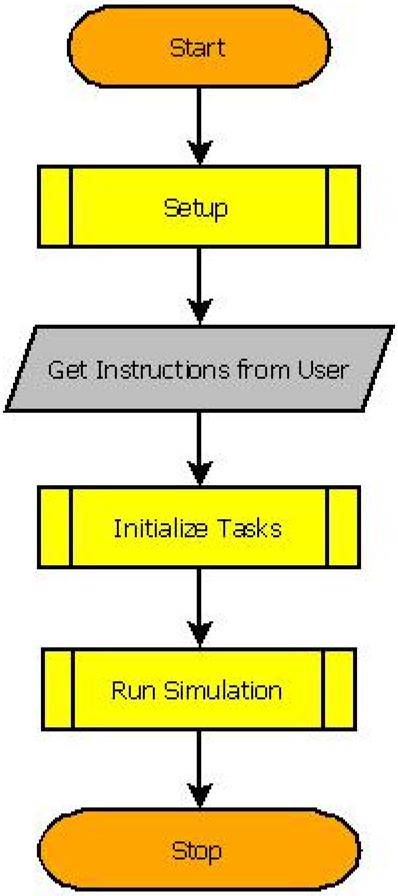


Figure 35: Flowchart of the general program structure.

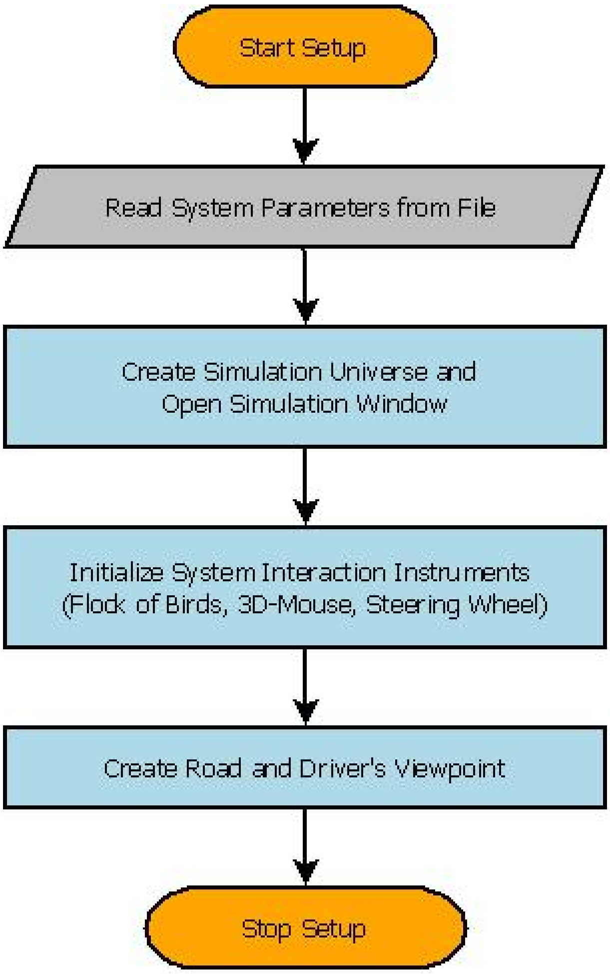


Figure 36: Flowchart of setup routine.

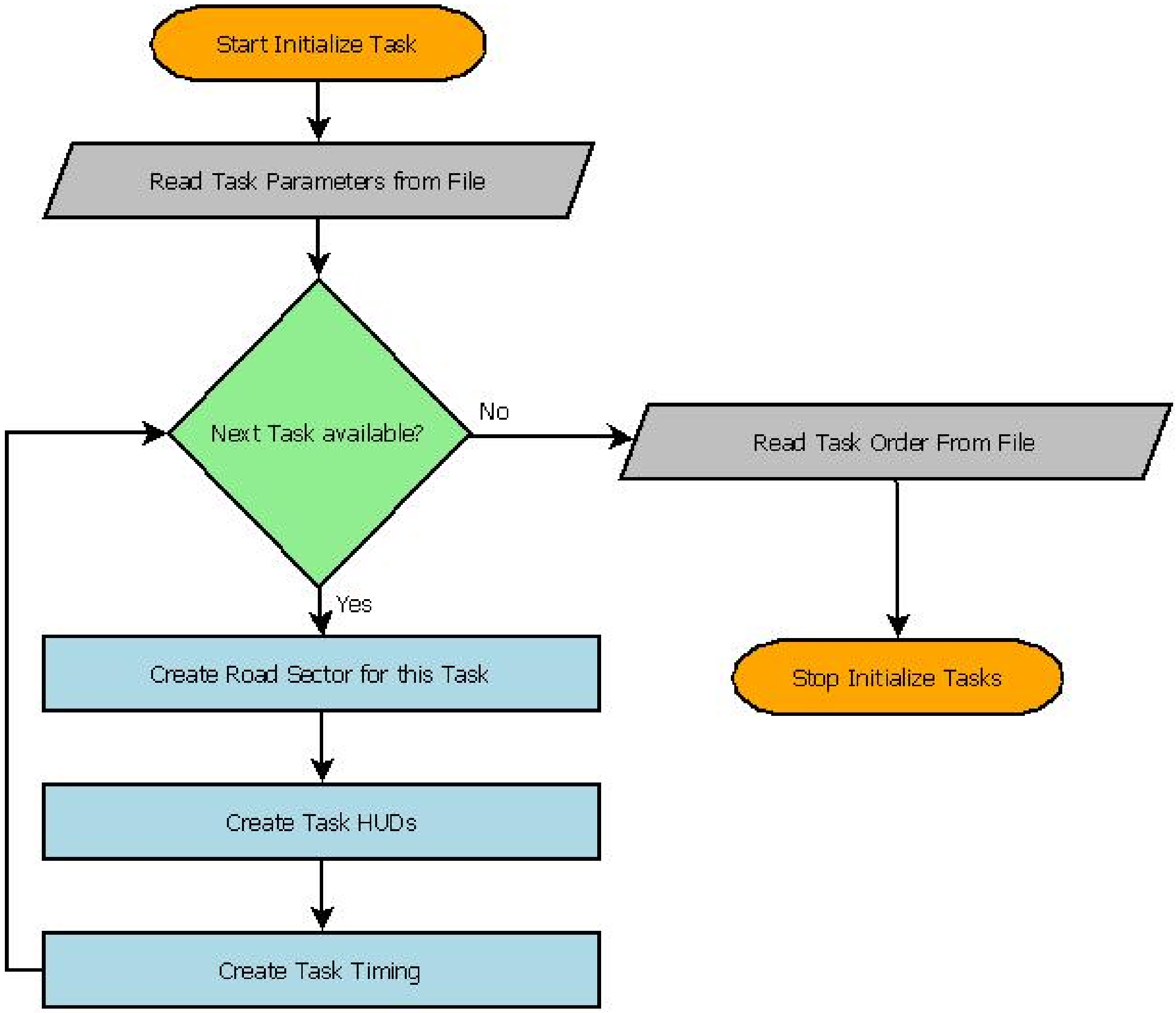


Figure 37: Flowchart of the task initialization procedure.

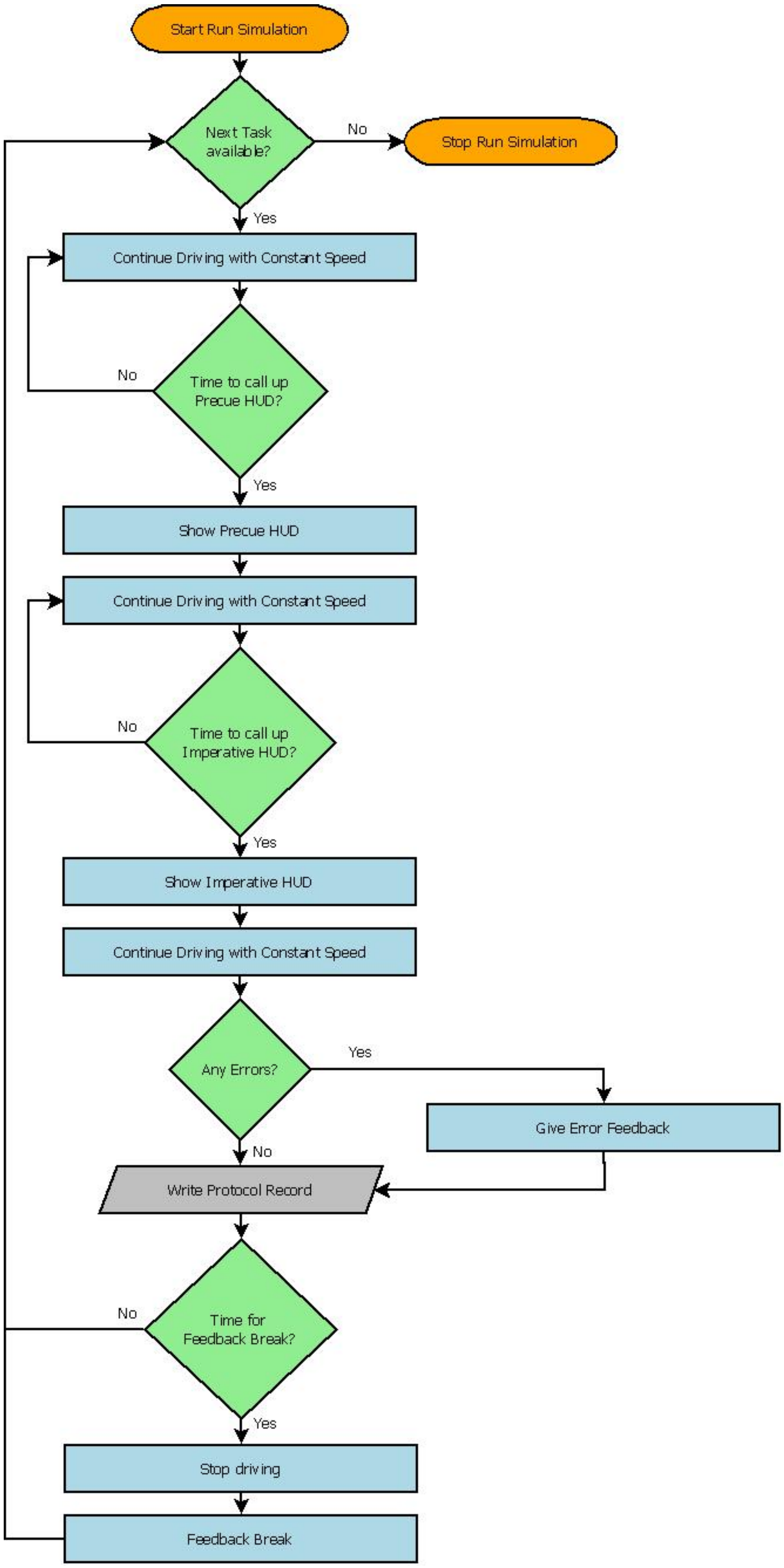


Figure 38: Flowchart of the simulation routine.