

Speed Perception and Speed Adaptation While Traveling in Passenger Cars

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Anna-Lena Köhler

Berichter: Univ.-Prof. Dr. phil. Iring Koch
Univ.-Prof. Dr.-Ing. Lutz Eckstein

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Abstract

Driving too fast is a major cause of accidents in everyday road traffic and is directly related to the severity of crashes. Drivers need to integrate a multitude of information and execute many tasks at the same time, with speed control being one of them. They frequently exceed speed limits, either willingly (e.g., because of personal or situational factors) or unintentionally. Conventional measures against speeding mostly focus on setting and enforcing speed limits, installing assistance systems in vehicles targeting the individual driver (e.g., speed limiters), or adapting the driving environment to foster lower driving speeds (e.g., speed humps or narrowed lanes). However, permanent interventions can lead to habituation or relevant cues can be overlooked, especially under high workload. Therefore, understanding the role of sensory information in speed perception can support the development of effective interventions. Visual information is the primary source of information in driving, while auditory information attracts attention faster and can reinforce (when both sources of information correspond) or limit (when both sources of information are in conflict) processing of visual information.

This thesis outlines the influence of visual and auditory stimuli on speed perception and speed adaptation in three studies. In Study I (Köhler et al., 2022), we researched speed adaptation in a static driving simulator study and subsequent field test. Light spots every few meters on both sides of the road of a motorway exit either remained static or were animated in a way to create the impression of moving towards drivers, thus targeting the optic flow: The stronger the optic flow, the higher the subjective impression of speed and, presumably, the more likely would be a self-imposed speed reduction. Results showed lower driving speeds in both light conditions compared to a baseline without lights, but only in the field test. To investigate the reasons for these findings, Study II (Köhler et al., 2023) was focused on speed perception and researched the underlying perceptual mechanisms of the same visuo-spatial stimuli in two subsequent laboratory studies using the method of constant stimuli. Results showed that speed was perceived as higher when participants encountered oncoming lights compared to static lights, but only when participants were not distracted by other visual stimuli, such as reflector posts or road markings. In Study III (Köhler et al., 2025), again in a laboratory setting using the method of constant stimuli to assess speed perception, the visuo-spatial stimuli were enhanced with corresponding auditory stimuli in the form of wind noise every time a light spot was passed. Again, speed was perceived as higher for oncoming stimuli, but bimodal stimulus presentation with corresponding stimuli had a considerably stronger

effect on speed perception. This suggests that studies with unimodal visual stimuli underestimated the potential for oncoming stimuli in mitigating driving speed, highlighting the potential of the presentation of corresponding bimodal stimuli for traffic safety.

Overall, results suggest that speed-related visual information in the studies of this dissertation influenced speed perception, that is, oncoming light stimuli created the impression that the driving environment moved by faster than it actually did by influencing the optic flow. Applying this to a countermeasure against speeding, drivers would be more likely to feel to be driving too fast for the traffic situation and decide to reduce their driving speed earlier than without such a countermeasure. However, this was only the case in the absence of additional visual stimuli that either contributed to the perception of the optic flow more prominently than the manipulated light stimuli or led to active processes such as counting reflector posts to estimate speed. Further, corresponding auditory information considerably reinforced visual information for oncoming stimuli and led to the impression of higher speed. This combination could lead to more effective interventions against speeding. Future research is needed to determine the effectiveness of bimodal stimulus presentation in the presence of additional stimuli that a speed estimation could be based on, and to replicate findings in naturalistic traffic.

Zusammenfassung

Überhöhte Geschwindigkeit ist eine der Hauptunfallursachen im Straßenverkehr und steht in unmittelbarem Zusammenhang mit der Schwere von Unfallschäden. Autofahrende müssen eine Vielzahl von Informationen verarbeiten und zahlreiche Aufgaben gleichzeitig ausführen. Eine davon ist die Kontrolle der Fahrgeschwindigkeit. Fahrende überschreiten häufig Geschwindigkeitsbegrenzungen, entweder absichtlich (z. B. aufgrund personenbezogener oder situativer Faktoren) oder unabsichtlich. Konventionelle Maßnahmen gegen überhöhte Geschwindigkeit konzentrieren sich meist auf die Festlegung und Durchsetzung von Geschwindigkeitsbegrenzungen, den Einbau von Assistenzsystemen in Fahrzeugen die sich direkt an die jeweiligen Fahrenden eines Fahrzeugs richten (z. B. Geschwindigkeitsbegrenzer oder intelligente Geschwindigkeitsanpassung), oder die Anpassung der Fahrumgebung, um geringere Fahrgeschwindigkeiten zu fördern, beispielsweise mithilfe von Bodenwellen oder Fahrbahnverengungen. Dauerhafte Maßnahmen können jedoch zu Gewöhnungseffekten führen oder es können relevante Hinweise übersehen werden, insbesondere unter hohem Workload. Daher kann ein besseres Verständnis der Rolle sensorischer Informationen bei der Geschwindigkeitswahrnehmung die Entwicklung wirksamer Maßnahmen unterstützen. Visuelle Informationen sind die primäre Informationsquelle beim Autofahren, während auditive Informationen Aufmerksamkeit schneller auf sich ziehen und die Verarbeitung visueller Informationen verstärken (wenn beide Informationsquellen übereinstimmen) oder einschränken können (wenn beide Informationsquellen in Konflikt stehen).

Die vorliegende Dissertation untersucht den Einfluss von visuellen und auditiven Stimuli auf die Geschwindigkeitswahrnehmung und Geschwindigkeitsanpassung in drei empirischen Studien. In Studie I (Köhler et al., 2022) wurde die Anpassung der Fahrgeschwindigkeit im Rahmen einer Studie in einem statischen Fahrsimulator und einer anschließenden Feldstudie untersucht. An einer Autobahnausfahrt leuchteten auf beiden Seiten der Fahrbahn in regelmäßigen Abständen von wenigen Metern Lichtspots entweder statisch auf oder wurden so angesteuert, dass der Eindruck entstand, dass sie sich auf die Fahrenden zubewegten. Damit sollte der sogenannte Optic Flow der Fahrenden beeinflusst werden: Je stärker der Optic Flow, desto höher der subjektive Geschwindigkeitseindruck und umso wahrscheinlicher ist, so die Annahme, eine selbstständige Geschwindigkeitsreduktion. Die Ergebnisse zeigten in der Feldstudie niedrigere Fahrgeschwindigkeiten bei beiden Lichtbedingungen im Vergleich zu einer Baseline ohne Lichtspots. Um die dahinterliegenden Gründe für dieses Ergebnis näher zu untersuchen, führten wir Studie II (Köhler et al., 2023) mit einem Fokus auf

Geschwindigkeitswahrnehmung durch. Hierbei wurden die zugrundeliegenden Wahrnehmungsmechanismen derselben visuell-räumlichen Stimuli in zwei Laborexperimenten unter Verwendung der Method of Constant Stimuli untersucht. Die Ergebnisse zeigten, dass die Teilnehmenden ihre Geschwindigkeit als höher wahrnahmen, wenn sie entgegenkommende Lichtspots im Vergleich zu statischen Lichtspots sahen. Dies traf jedoch nur zu, wenn die Probanden nicht durch weitere visuelle Stimuli wie Leitpfosten oder Straßenmarkierungen abgelenkt wurden. In Studie III (Köhler et al., 2025), ebenfalls unter Laborbedingungen und unter Anwendung der Methode der konstanten Stimuli, wurde immer dann ein übereinstimmender auditiver Stimulus in Form von Windgeräuschen dargeboten, wenn ein Lichtspot passiert wurde und die visuell-räumlichen Stimuli dadurch verstärkt. Auch hier wurde die Geschwindigkeit bei entgegenkommenden Stimuli als höher wahrgenommen, aber bimodale übereinstimmende Stimuli hatten einen wesentlich stärkeren Effekt auf die Geschwindigkeitswahrnehmung. Dies deutet darauf hin, dass Studien mit unimodalen visuellen Stimuli das Potenzial von entgegenkommenden Stimuli zur Verringerung von Fahrgeschwindigkeit unterschätzten, was das Anwendungspotenzial einer entsprechenden bimodalen Stimuluspräsentation für die Verkehrssicherheit unterstreicht.

Insgesamt deuten die Ergebnisse dieser Dissertation darauf hin, dass geschwindigkeitsbezogene visuelle Informationen in den durchgeführten Studien die Geschwindigkeitswahrnehmung beeinflussten, d.h. entgegenkommende Lichtspots erweckten durch die Beeinflussung des Optic Flow den Eindruck, dass die Fahrumgebung schneller vorbeizog als sie es tatsächlich tat. Übertragen auf eine zu entwickelnde Gegenmaßnahme gegen Geschwindigkeitsübertretungen würden Autofahrende eher das Gefühl haben, für die Verkehrssituation zu schnell zu fahren, und sich frühzeitiger zu einer Geschwindigkeitsreduktion entschließen. Dies war jedoch nur dann der Fall, wenn keine zusätzlichen visuellen Reize vorhanden waren, die entweder mehr als die experimentellen Stimuli zur Wahrnehmung des Optic Flow beitrugen oder zu aktiven Handlungen wie dem Zählen von Leitpfosten zur Einschätzung der Geschwindigkeit führten. Darüber hinaus verstärkten übereinstimmende auditive Informationen die visuellen Informationen für entgegenkommende Stimuli und führten zu einem höheren Geschwindigkeitseindruck. Diese Kombination könnte zu wirksameren Maßnahmen gegen Geschwindigkeitsüberschreitungen führen. Künftige Forschung sollte die Wirksamkeit der bimodalen Stimuluspräsentation bei konkurrierenden Stimuli untersuchen und die Ergebnisse im realen Straßenverkehr replizieren.

Overview of Scientific Publications

Study I

Köhler, A.-L., Koch, I., & Ladwig, S. (2022). Guiding drivers towards safer driving speed: Exploiting visual dominance in speed adaptation. *Transportation Research Part F: Traffic Psychology and Behaviour*, 90, 438-450. <https://doi.org/10.1016/j.trf.2022.09.011>

Study II

Köhler, A.-L., Klatt, M., Koch, I., & Ladwig, S. (2023). Investigating the influence of visuospatial stimuli on driver's speed perception: A laboratory study. *Cognitive Research: Principles & Implications*, 8(1), 59. <https://doi.org/10.1186/s41235-023-00513-x>

Study III

Köhler, A.-L., Koch, I., & Ladwig, S. (2025). Investigating the role of visual and corresponding auditory stimuli in driving-related speed perception. *Transportation Research Part F: Traffic Psychology and Behaviour*, 110, 1-14. <https://doi.org/10.1016/j.trf.2025.02.007>

Declaration of Authorship

I, **Anna-Lena Köhler**, hereby certify that this cumulative dissertation has been composed by me and is based on my own work. I conceptualized the studies, supervised the programming of the experiments, oversaw data collection, conducted the statistical analyses, and wrote the included scientific papers and manuscripts. My supervisors **Univ.-Prof. Dr. phil. Iring Koch** and **Dr. phil. Stefan Ladwig** were involved in the conceptualization of the studies and provided guidance with the constitution of the papers and manuscripts. **Maren Klatt** was involved in the constitution of one manuscript and supported the preparation and conduction of the respective experiments (Köhler, Klatt, Koch, & Ladwig, 2023). **Univ.-Prof. Dr.-Ing. Lutz Eckstein** was involved in the overall setup of this dissertation and provided the research infrastructure.

1 Introduction

Participating in road traffic is an everyday activity for many people. However, traffic injuries are the leading cause of death for children and young people and rank as the twelfth leading cause of deaths for the entire population worldwide, with 1.19 million fatalities and up to 50 million people injured in traffic every year (World Health Organization, 2023a). Road traffic fatalities for Europe are already the lowest worldwide. In 2023, the latest numbers available from the World Health Organization (WHO) at the time of the publication of this manuscript, 50 % of road traffic deaths in Europe were car occupants (highest rate in comparison to other regions worldwide), followed by pedestrians (25 %), occupants of motorized 2- and 3-wheelers (12 %), cyclists (6 %), and others (7 %; World Health Organization, 2023a).

The five major behavioral risk factors for traffic accidents are a lack of seat-belt use, high driving speed, lack of helmet use, drink-driving, and lacking child restraints. The traveling speed of a vehicle is a direct influencing factor on the risk of a crash (see *Word Choice Matters: Crash vs. Accident*, 2023), as well as the severity of injuries, and the likelihood of dying in a traffic crash (World Health Organization, 2023a). Even though Europe has the lowest rate of road traffic accidents worldwide, high driving speed is a major cause for crashes in the European Union (European Commission, 2024). Initiatives such as Sweden's Vision Zero from 1997 (*Vision Zero - no fatalities or serious injuries through road accidents*, 2019), which has meanwhile been adopted by the European Commission and many individual countries (for an extensive overview, see Björnberg et al., 2019), focusing on no deaths and serious injuries in traffic, or the WHO's Safe LIVES aim at a Safe System Approach. Vision Zero was developed under the assumption that people always make mistakes that can lead to crashes, that the human body can only tolerate a certain amount of kinetic energy before injuries and fatalities occur, and that traffic participants should act responsibly and abide by traffic laws. At the same time, road authorities and everyone involved in traffic, development of roads, and vehicles are encouraged to work towards preventing crashes. Further, all these parts of the Safe System should be strengthened in combination to provide a safety net for road users in case a part of the system fails (World Health Organization, 2017). The Safe LIVES program, on the other hand, mainly focuses on technical solutions including infrastructure design and improvement (self-explaining roads, SER; e.g., Theeuwes, 2021), vehicles needing to meet safety standards, or speed management. The latter includes, for example,

speed limit laws, modification of roads, or requiring manufacturers to develop and install technologies to support drivers in keeping speed limits (World Health Organization, 2017).

For effective implementation of these guidelines and to facilitate development of interventions to reduce driving speed, it is crucial to understand how speeding occurs and which factors have an influence on both speed adaptation and, in conclusion, speed perception. Hence, it is necessary to understand the role of human sensory dynamics to develop suitable interventions.

This dissertation contributes to determining the role of sensory information in human perception and adaptation of driving (related to when someone is driving themselves) or traveling speed (related to when someone is not necessarily driving themselves but rather perceives how fast a vehicle “travels”) in traffic. It includes three empirical studies, Study I on speed adaptation in a static driving simulator and in naturalistic traffic and Studies II and III on speed perception in a laboratory setting.

In chapter 1, I will first outline the driving task and the role of human information processing in this context (chapter 1.1), followed by interventions to mitigate driving speed that have been researched so far by using both conventional and innovative approaches, such as nudging (Thaler & Sunstein, 2008). Furthermore, I will describe factors influencing the selection and adaptation of driving speed, especially on perceptual influences on human speed perception focusing on visual and auditory influencing factors. After providing this theoretical framework, I will outline the findings of the empirical studies in chapter 2. In chapter 3, I will give a summary of the insights into human speed perception (chapter 3.1), discuss aspects for future research (chapter 3.2), and provide an overall conclusion (chapter 3.3).

This dissertation should be easy to understand also for readers who might wish to read only selected sections due to personal research interest in the covered topics. Therefore, readers of the full manuscript might encounter occasional redundancies.

1.1 Driving Task

Drivers need to execute numerous sub-tasks at the same time when driving a car (Stapel et al., 2019), such as lateral or longitudinal tracking, which are usually researched separately, since each sub-task is based on different theoretical frameworks (Papakostopoulos et al., 2017). Driving performance can be determined by many different indicators. Relevant variables that have each been described to be relevant for different sub-tasks in driving are, for example, time-to-collision (TTC), time-to-line-crossing (TLC; for an overview and critical assessment, see Green, 2013), or the optical edge rate (e.g., Rakauskas, 2009).

Furthermore, there is a lot of information available to drivers, which is potentially relevant for executing the driving task that needs to be integrated, such as distance perception cues (for an overview, see Papakostopoulos et al., 2017). The latter are especially relevant for longitudinal tracking, which describes aspects such as speed perception and speed selection. This is described in more detail in the subsequent chapter 1.2.

Besides longitudinal tracking, lateral tracking is another important purpose when driving, describing the task to follow the road (Papakostopoulos et al., 2017). This includes steering wheel control (e.g., standard deviation of steering wheel angle, steering wheel reversal rate; Papantoniou et al., 2017), or staying in a position on the lane that feels safe for the individual driver (which depends on, e.g., oncoming traffic or driving speed; for an overview see Voß, 2020) and which requires little mental resources (Michon, 1985). In a driving simulator study by Cooper et al. (2013), drivers usually drove in the direction of their gaze and looked more centrally with increased cognitive workload due to higher gaze concentration on objects right in front of them. Furthermore, lateral tracking also includes approaching and following curves. Drivers on a test route typically focused on the occlusion point, which was described as the closest point where the view of the road was blocked by an obstacle (Lehtonen et al., 2012), or other points ahead of their way of driving within one to two seconds (Lehtonen et al., 2013). Drivers alternated looking at the occlusion point with focusing on the road directly ahead of them. However, the higher the cognitive workload, the less likely the drivers were to check their speedometer or mirrors (see Lehtonen et al., 2012, for an overview).

These findings provide a first impression that a multitude of information needs to be processed and integrated when driving. This includes especially auditory and visual information (e.g., Palmisano, 2002, see chapter 1.3), information from vestibular or other proprioceptive (Kemeny & Panerai, 2003; Reymond et al., 2001), kinaesthetic (Macadam, 2003), and haptic sources (Sigrist et al., 2013). Hence, driving requires multitasking. However, the human information processing system is capacity-limited (Kahneman, 1973), so processing and integrating multiple sources of information has certain limitations. Multiple-resource theory (e.g., Wickens, 2008) described that tasks can be executed in parallel without competing for the same cognitive resources when perceptual modality, processing codes, processing stages, and motor modalities differ. Perceptual and motor modality describe in which modality information is perceived and which modality is relevant for execution. Processing codes define how something is being perceived, that is, spatial or verbal, while processing stages describe the levels perception, decision or response selection, and motor execution. In driving, however, information that needs to be processed often competes for the same resources

(i.e., working memory; Lehtonen et al., 2012), for example, in busy traffic situations, where drivers need to react to several cues at once. In consequence, drivers need to allocate resources to meet task demands, which usually vary based on the complexity of a traffic situation (e.g., Stapel et al., 2019). However, the debate about the degree of interference in such multitasking situations and the underlying cognitive mechanisms is still ongoing (see Koch et al., 2018). In addition, in-depth research on sensory dynamics has been limited especially for the driving context and when developing driver models (Nash et al., 2016). Therefore, this dissertation aims at understanding sensory influences on the perception of driving speed as one aspect of driving.

1.2 Driving Speed

Longitudinal tracking (Papakostopoulos et al., 2017) or control of a vehicle describes tasks that refer to the driving speed. This is especially relevant when it comes to road safety (e.g., Aarts & van Schagen, 2006; Quddus, 2013; World Health Organization, 2023a). Drivers generally are believed to aim at staying safe in traffic and keeping up safety margins (field of safe travel (FosT) hypothesis, Gibson & Crooks, 1938; Papakostopoulos et al., 2017). The FosT hypothesis focused on drivers' subjective impression of being safe in traffic and their efforts to keep their car in the middle of this objectively measurable field, in which a vehicle can be operated safely (e.g., Gibson & Crooks, 1938; Kolekar et al., 2020). More precisely, they used time-to-line-crossing (TLC) as the variable that it takes the vehicle to cross the lane boundaries when both velocity and the steering wheel are held steadily (Gibson & Crooks, 1938; Melman et al., 2018). In another approach, Taylor (1964) described that drivers adjust their speed so that their crash risk remains constant, leading to lower driving speeds in more challenging conditions (see also Melman et al., 2018). Both approaches assume that drivers aim at staying safe in traffic. So why do we see speed-related crashes and therefore the need to develop interventions against speeding?

Most countries have speed limits for highways, expressways, country roads, and within cities, with Germany being one of few countries without a general speed limit on highways (*Speed limit by country*, 2024). These take the margin of safety into account, which includes the difference between actual and required friction on the road including tangential and radial friction (Köhler et al., 2019; Pratt et al., 2015). Following speed limits has a positive impact on traffic safety (Elvik et al., 2004). However, when it comes to driving speed, drivers at present still decide to drive too fast for a given situation (European Commission, 2022). About 50 % of drivers in a survey admitted exceeding speed limits (Yannis et al.,

2013). On the one hand, personal factors like driving style (Iftikhar et al., 2020) or attitude towards speeding (Wiafe et al., 2020) could affect driver's reactions in traffic. Previous research suggested that young drivers were more likely to drive aggressively (Perepjolkina & Renge, 2011; Shope & Bingham, 2008) and that older drivers usually showed more behavior of safer driving such as observance of speed limits (Shinar et al., 2001). Also, higher annual mileage was associated with more aggressive driving (Perepjolkina & Renge, 2011). On the other hand, situational factors, for example, time pressure or social factors like feeling pressured by a peer (Wiafe et al., 2020) or other drivers (Haglund & Åberg, 2000) to drive faster, or the belief that others break speed limits as well (Yannis et al., 2013) could influence speed selection. However, drivers were found to be more sensitive to cues and less influenced by individual factors the more experienced they became (Xu et al., 2014). Generally, even when drivers knew that a lower speed would be safer, they might have willingly decided to leave their comfort zone or their field of safe travel and accept a higher risk (Bärgman et al., 2015).

These examples so far give the impression that people are mostly aware of exceeding speed limits. However, there could be situations where drivers might not perceive that they are driving at an unsafe speed (Groeger & Grande, 1996; Kuiken & Twisk, 2001; Truelove et al., 2022). Hence, in addition to conventional interventions to mitigate driving speed, especially perceptual factors influencing human speed perception play a vital role and need to be understood to facilitate successful development of interventions aiming at safer driving speeds.

1.2.1 Mitigating Driving Speed

When it comes to safe driving speed, a variety of solutions to mitigate driving speed have been researched and already implemented, both inside vehicles and in the infrastructure. Setting an appropriate speed limit and enforcing it is certainly the most established and proven intervention (World Health Organization, 2023b). Promising interventions inside vehicles include speed limiters, intelligent speed adaptation, autonomous emergency braking, or electronic stability control (Fisa et al., 2022; World Health Organization, 2023b). Furthermore, adaptive interventions have been researched that scan the driving environment for potentially hazardous situations and warn drivers accordingly (e.g., Aust et al., 2020).

Interventions in vehicles target the individual driver, while interventions implemented in the infrastructure target every driver passing the site. This could be especially interesting for crash hotspots where high driving speed is the main issue for potentially hazardous traffic situations (Köhler et al., 2019). More specifically, the driving environment itself has an

influence on driving speed (Dumbaugh et al., 2020). For example, converting intersections to roundabouts decreased the number of crashes in these locations (Fisa et al., 2022; World Health Organization, 2023b). Further interventions in the infrastructure that have shown promising results include, for example, speed humps, narrowed lanes, or gateways at the entrance to towns and villages that clearly signal that lower driving speeds are in order (i.e., via large signs, vertical pavement markings, and architectural or landscaping treatments; Abdel-Aty et al., 2024; Charlton et al., 2010; World Health Organization, 2023b). Similar interventions include lines that are painted on the road (Ding et al., 2020; Bergh Alvergren et al., 2019; Gates et al., 2008; Thaler & Sunstein, 2008) or on tunnel walls (Manser & Hancock, 2007) that get closer and closer together, or lower lane width leading to lower driving speeds (Godley et al., 2004; Melman et al., 2018). Consequently, the impression of wider spaces, for example, on highways, likely benefits higher driving speeds (Abdel-Aty et al., 2024). A very effective intervention to reduce the speed of low-risk drivers in a simulator study were dragon's teeth, while high-risk drivers were hard to influence by pavement markings at all (Lee et al., 2013). So, the latter would be more inclined to decide accepting a higher risk (e.g., Bärghman et al., 2015) but might be hard to influence with similar interventions at all (Lee et al., 2013). However, adding visual stimuli to the driving environment has generally been found to decrease driving speed (e.g., Köhler et al., 2022; Pretto & Chatziastros, 2006).

In this context, the Safe System Approach (World Health Organization, 2017, 2023b; Theeuwes, 2021) underlined that the design of the driving environment makes it easy for traffic participants to behave safely. However, specific interventions that are displayed permanently could lead to habituation (Gates et al., 2008; Hautzinger et al., 2011). Relevant cues in the driving environment could be overlooked, especially when drivers followed established behaviors or are under high workload (Theeuwes, 2021), or when drivers willingly decided to drive more riskily (see chapter 1.2, e.g., Bärghman et al., 2015; European Commission, 2022; Lee et al., 2013). This is where more adaptive interventions to mitigate driving speed might come into play, which form the base for this dissertation and will be described in the following.

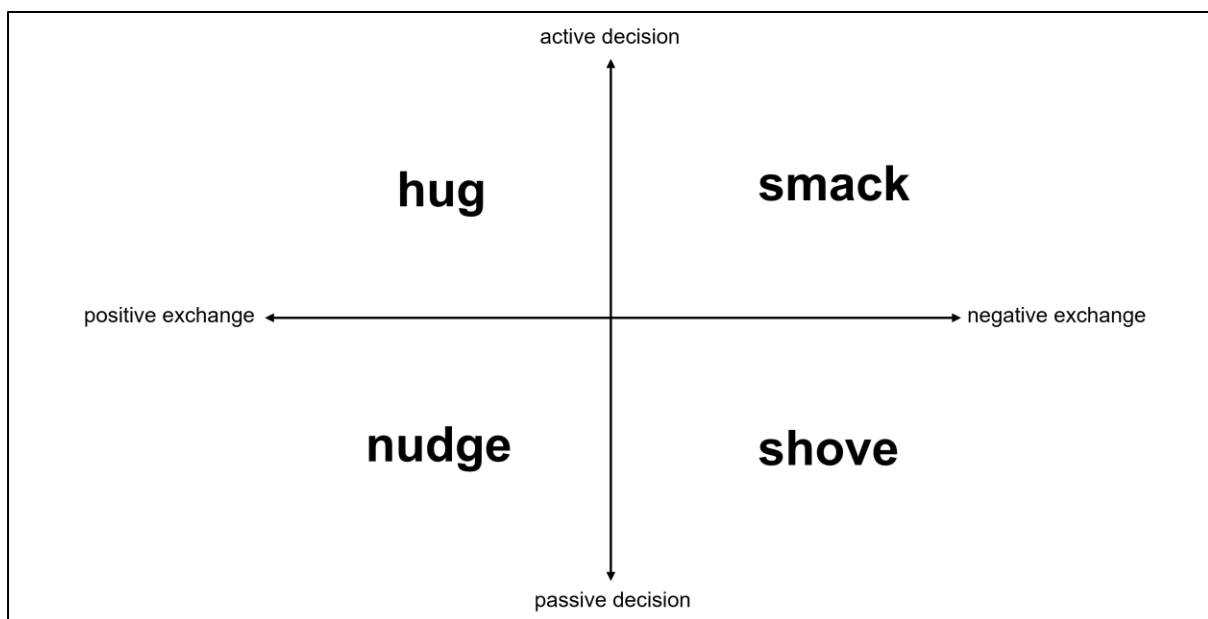
1.2.2 Nudging Drivers Towards Safer Driving Speed

French (2011) categorized interventions that manage driving speed into four forms of exchange that are either based on an active or passive decision and either a positive or negative exchange, see Figure 1. In this framework, a smack and a shove were described as situations where people experience a negative consequence for their behavior. In the case of a

smack, this is delivered after the behavior, for example, getting a ticket for speeding. A shove, on the other hand, is delivered before or while the behavior occurs, for example speed humps. A hug was described as a positive invitation to, for example, drive slower by rewarding the active decision for this by, for example, showing a positive smiley to all drivers that follow the speed limit at a certain location, again being delivered after the positive behavior has been shown. Lastly, a nudge intends to positively shape behavior before it occurs. In the case of driving speed, this is done by shaping the driving environment to facilitate safe driving, like the previously described Safe System Approach (e.g., World Health Organization, 2017, 2023b; Theeuwes, 2021). While negative exchanges serve as punishment for undesired behavior such as speeding, positive exchanges either reward safe behavior (i.e., a hug) or prevent unsafe behavior (i.e., a nudge). The stimuli described in this dissertation to research the influence of visual and auditory stimuli on speed adaptation and perception are based on the concept of nudging, since they aim at influencing speed perception to prevent higher and potentially unsafe driving speeds.

Figure 1

Four forms of exchange along the continuums of active/passive decision and positive/negative exchange (French, 2011, p. 159).



The concept of nudging comes from behavioral economics and has been revived by the book “Nudge – Improving decisions about health, wealth and happiness” (Thaler & Sunstein, 2008). The concept aims to support people to make better decisions. Traffic participants

might drive at an unsafe speed without intending to or being aware of it (Karlsson et al., 2017; Kuiken & Twisk, 2001). Reasons for this could be, for example, unpredictable road layouts or traffic congestion (see Karlsson et al., 2017) or even low situational awareness (Endsley, 2021; Jones & Endsley, 2004). A nudge (as one form of exchange; French, 2011) provides the prerequisites for future positive or, in this case, safe (driving) behavior and supports people in following a desired behavior (Thaler & Sunstein, 2008). This can either be self-imposed, for example, by putting a large bottle of water on the table to encourage oneself to drink more, or imposed by others, for example, by putting the salad bar in canteens near the entrance to foster healthier diet choices. People can still decide to take the fries that come later, but it is more likely that they will already have put some salad on their tray and might decide against the fries (House et al., 2013, see Karlsson et al., 2017, for a detailed overview).

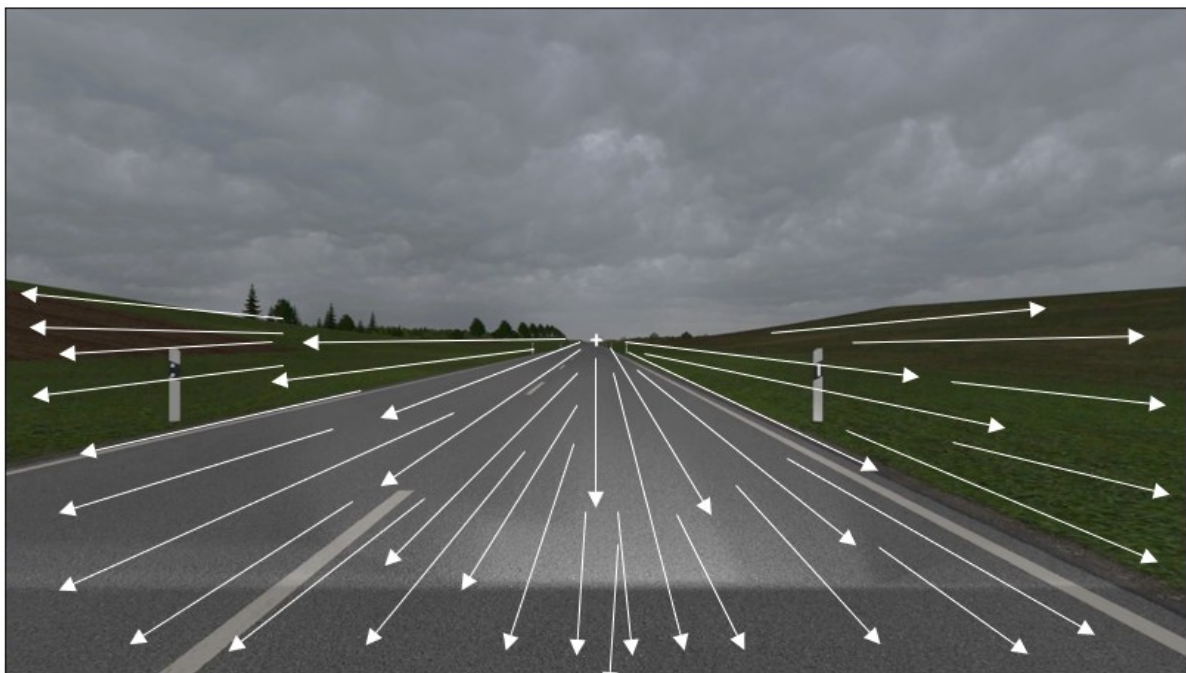
Transferred to a situation in which drivers might be likely to adapt an inappropriate speed, transverse-bar road markings that are gradually getting closer and closer towards each other can nudge drivers to adapt a lower speed, because they might feel that they are driving faster than they actually do and might see the need to slow down (Thaler & Sunstein, 2008). This is where the MeBeSafe-project (Masures for Behaving Safely in Traffic) started, which also provided the starting point for this dissertation. The project within the HORIZON 2020-call by the European Commission developed and tested, among other measures, a solution to nudge drivers towards adopting safer driving speed by nudging them via a dynamic nudging solution with light spots in the infrastructure. The solution detected vehicles that were driving faster than at least 10 % above the speed limit and activated lights in front of the vehicle either with or without a movement component towards the vehicle (see Köhler et al., 2019, 2022). The solution showed promising results, that is, drivers slowing down when experiencing the intervention in comparison to a baseline (see chapter 2.1; Köhler et al., 2019, 2022). What remained open, however, was an explanation why drivers reduced their speed and how the intervention might have affected human speed perception. Hence, this dissertation aspires to explain the role of sensory dynamics in human speed perception and aims to go beyond the mere “slowing down”. Instead, it aims at explaining the “why” to provide more details for the development of innovative interventions to reduce speeding. The following chapter provides an overview of how humans perceive (especially driving and traveling) speed.

1.3 Human Speed Perception

Whenever we as humans are moving, we experience this movement relative to our environment (Palmisano, 2002; Pretto & Chatziastros, 2006). This is amplified when sitting in a moving vehicle (Feria et al., 2003; Higuchi et al., 2020; Palmisano, 2002) and has been described in the optic flow paradigm (Gibson, 1950): The cues in the environment pass by and this leads to a perception of movement, see Figure 2.

Figure 2

Illustration of the optic flow paradigm based on Higuchi et al. (2020, p. 579), taken from Köhler et al. (2025, p. 2).



The previously described studies to mitigate driving speed by, for example, painting lines on the road or tunnel walls used this paradigm (see chapter 1.2.1): Lines that get closer and closer together likely created the impression that drivers felt that they were driving faster than they actually did, thus prompting them to slow down (e.g., Köhler et al., 2019). This intervention to mitigate driving speed targeted drivers and their speed selection and potentially influenced speed perception. But which factors do exactly influence the perception of driving or traveling speed?

Next to the visual information described in the context of the optic flow (Feria et al., 2003; Gibson, 1950; Palmisano, 2002), further perceptual information, such as auditory or

haptic cues and their interaction have been found to influence driving speed and speed perception (Papakostopoulos et al., 2017; see chapter 1.1). However, when processing speed related information, the visual and the auditory modality were dominant (Horswill & McKenna, 1999). Generally, visual attention was described to require active allocation while processing of input from other sources was limited (e.g., Posner et al., 1976), while auditory information attracted attention faster (e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014; Shams et al., 2002). Drivers most likely focus on what they see while driving, because this information is crucial to execute the driving task safely. On the other hand, this limits the processing of other available information. Relevant auditory information, on the other hand, can attract the driver's attention. Here, visual and auditory information are part of different processing codes (Wickens, 2008; see chapter 1.1 for more details).

Since the human information-processing system is generally understood to be capacity limited (Kahneman, 1973), this leads us back to the necessity to allocate resources to meet task demands of the driving task (e.g., Stapel et al., 2019; see chapter 1.1 for more details). How drivers perceive driving speed and control the vehicle is also influenced by, for example, their hypotheses about the driving environment, potential hazards, and behavior of other road users (Papakostopoulos et al., 2017). Therefore, researching all influences on human speed perception is a complex task that goes beyond the scope of this dissertation. Focusing on individual components is a first step in understanding influences on speed perception and can provide a background for developing interventions for safer driving.

When driving a vehicle, we are monitoring where we are driving (e.g., Gibson, 1950; Krüger et al., 1999). Therefore, *visual information* is a primary source of information when driving (Macadam, 2003) and visual stimuli in the driving environment have been found to influence driving and traveling speed (e.g., Abdel-Aty et al., 2024; Gates et al., 2008; Köhler et al., 2022, 2023; Manser & Hancock, 2007; Pretto & Chatziastros, 2006; see chapter 1.2.1). Visual stimuli can be linked to the spatial dimension (e.g., Lukas et al., 2014), since stimuli in the different perceptual modalities are perceived through corresponding dimensions (modality appropriateness hypothesis, Welch & Warren, 1980). For example, vision was more prominent than other perceptual sources for spatial localization tasks (Ward et al., 2000), such as auditory information (Lukas et al., 2010; Lukas et al., 2014). In general, drivers usually monitor where they are going and likely also how fast they are driving while executing the driving task (Papakostopoulos et al., 2017). Speed control can therefore be characterized as a spatial control task (e.g., Köhler et al., 2022). However, objectively driven speed and the subjective impression of speed (Denton, 1980) or estimation of distances (Wu et al., 2004) might not

correspond. A relatable example has been described by the speed adaptation effect (Denton, 1966), which outlined the feeling of driving particularly slowly when slowing down after traveling at higher speeds for a longer period. Driving in a 30 km/h zone might feel more like driving in a play street with a speed limit around walking pace after coming from a highway with much higher speeds in comparison to having just started a drive. Generally, drivers tended to underestimate their own driving speed and the speed of oncoming cars by 20 %, suggesting that speed perception is subject to perceptual biases (Schütz et al., 2015). Hence, a more detailed understanding of how visual cues in the driving environment could influence speed perception and speed selection could aid in developing interventions to help drivers select safer driving speeds.

Next to visual stimuli, *auditory information* was found to be a highly relevant modality for processing information on (driving) speed and was especially relevant when drivers tended to not look at their speedometers (Horswill & McKenna, 1999). In driving, auditory information may consist of wind noise, the sound of tires on the asphalt (Denjean et al., 2012; Fischer et al., 2012), or a higher vehicle noise in the car (Merat & Jamson, 2011), which all led to lowered driving speeds. Generally, an assumed advantage in processing visual input compared to other sensory input modalities has been reported, often referred to as visual dominance (e.g., Ernst & Banks, 2002; Ladwig et al., 2012, 2013), which, for example, Lukas et al. (2010) demonstrated with shorter reaction times (RT) to visual stimuli in a multitasking paradigm with simultaneously presented bimodal visual and auditory stimuli. Auditory information not only attracted attention faster (e.g., Lukas et al., 2014) but also limited processing of visual information when both sources of information were in conflict (temporal ventriloquism, e.g., Manabe & Riquimaroux, 2000; Morein-Zamir et al., 2003; Shams et al., 2002, 2004). It also reinforced information from the visual modality when the two sources of information corresponded (Calabro et al., 2011; Gagliano, 2016; Keshavarz et al., 2014; Köhler et al., 2025; Recanzone, 2003). Auditory cues intensified the effect ofvection, describing visually induced self-motion (e.g., Gagliano, 2016; Keshavarz et al., 2014). In the driving context, corresponding visual and auditory information resulted in a more accurate speed estimation (Ramkhalawansingh et al., 2016).

This dissertation therefore researches the influence of visual and auditory stimuli in the driving environment on human perception. Since visual stimuli have been described as the major source of information in driving (e.g., Gibson, 1950; Macadam, 2003), the influence of visual stimuli on speed adaptation (Study I – Köhler et al., 2022) and speed perception (Study II – Köhler et al., 2023) was investigated first. For this, we applied visual stimuli

in the form of both static and oncoming lights on the road surface. On the one hand, the oncoming lights aimed at influencing the optic flow (e.g., Gibson, 1950) and thus giving participants the impression that they would be driving faster than they actually do, leading to them reducing their speed because of feeling to be driving too fast for the traffic situation. The static lights, on the other hand, were tested to isolate the suspected effect of the movement component on speed perception from a general influence of the light stimuli on speed adaptation and perception per se. Subsequently, we focused on the influence of corresponding bimodal stimuli, that is, auditory stimuli in the form of wind noise, whose conveyed information corresponded to that of visual stimuli (Study III – Köhler et al., 2025). I describe this in the following chapter 2.

2 Summary and Discussion of the Empirical Contributions to this Thesis

In the following chapter, I will give an overview of the executed studies. I will first outline the development and testing of an adaptive intervention to mitigate driving speed with visual stimuli in the form of lights in a simulator experiment and subsequent field test (Study I, chapter 2.1). Here, the focus lies on speed adaptation of drivers in response to visual stimuli on the road level that were activated with or without a movement component of moving towards the driver. In the subsequent Study II (chapter 2.2), we investigated the influence of the stimuli tested in Study I on perception of traveling speed (since participants did not drive themselves) instead of speed adaptation. Participants saw video sequences to research the influence of sensory factors on speed perception by using the method of constant stimuli (Hegelmaier, 1852, cited by Laming & Laming, 1992) in a laboratory setting. Study II was tested in two experimental parts. Lastly, in Study III (chapter 2.3), we added corresponding auditory information to the visual stimuli from Study II to investigate the role of additional auditory stimuli in human speed perception. This was again tested via video sequences in a laboratory setting.

Table 1 illustrates the structure of the empirical studies. It outlines the context in which each study was tested and summarizes the main findings.

Table 1

Structural overview of the three studies of this thesis, illustrating the research topic, testing context and stimuli, and main findings. Main differences between the studies are highlighted.

Study	Research focus	Method	Main findings
I. Köhler, A.-L., Koch, I., & Ladwig, S. (2022)	Influence of visual stimuli based on the optic flow on speed adaptation	Driving simulator study: Static and oncoming lights, baseline without lights Field test: Static and oncoming lights, baseline without lights	- No difference in driving speed in response to static or oncoming light stimuli compared to a baseline in the driving simulator. - Lower driving speeds in both light conditions compared to a baseline in the field test, but no difference between light conditions.
II. Köhler, A.-L., Klatt, M., Koch, I., & Ladwig, S. (2023)	Influence of visual stimuli based on the optic flow on speed perception	Experiment 1A: Video sequences of static and oncoming lights with lane markings and reflector posts Experiment 1B: Video sequences of static and oncoming lights without lane markings and reflector posts	- Higher perceived speed in sequences with oncoming stimuli only in the absence of lane markings and reflector posts. This suggests an influence of visual stimuli on speed perception based on the optic flow only in the absence of additional visual stimuli.
III. Köhler, A.-L., Koch, I., & Ladwig, S. (2025)	Influence of corresponding visual and auditory stimuli based on a combined optic and acoustic flow and their influence on speed perception	Experiment 1A: Video sequences of static and oncoming light stimuli, either unimodal (visual stimuli without engine sound) or bimodal (corresponding visual and auditory stimuli, with engine sound) Experiment 1B: Video sequences of static and oncoming light stimuli, either unimodal (visual stimuli with engine sound) or bimodal (corresponding visual and auditory stimuli, with engine sound)	- Replication of higher perceived speeds for oncoming stimuli compared to static stimuli in both experiments (replication of Study II, Experiment 1B). - Speed reduction for oncoming stimuli was more than twice as large with corresponding bimodal visual and auditory stimulus presentation. Corresponding auditory information reinforced visual information. - Auditory stimuli alone influenced speed perception.

2.1 Study I: Influence of Visuospatial Stimuli on Speed Adaptation

A variety of interventions target drivers adapting a driving speed that is too high, many of them permanently by, for example, converting the driving environment (see chapter 1.2.1) to make it easier for drivers to behave safely (World Health Organization, 2017, 2023b; Theeuwes, 2021) before even behaving unsafely (French, 2011; Karlsson et al., 2017). Such permanent interventions, however, could lead to habituation effects (e.g., Hautzinger et al., 2011). To address this problem, we led the development of an adaptive infrastructure intervention to target only those drivers that are driving too fast at a certain location, focusing primarily on habitual speeders who might be unaware of potential risk due to their driving speed (see Karlsson et al., 2017; Köhler et al., 2019). The conceptual development of the intervention and testing of its effect on speed adaptation is described in Köhler et al. (2022).

Because visual stimuli are a primary source of information in driving (see chapter 1.3, e.g., Macadam, 2003) and speed selection (see chapter 1.2.1; e.g., Gates et al., 2008; Manser & Hancock, 2007), we assumed that an intervention for drivers that are driving too fast for a given situation would benefit most from visual cues. However, research on sensory dynamics in speed perception has been limited so far (see Nash et al., 2016). Hence, understanding sensory dynamics in speed perception could help in the development of interventions especially targeting drivers who might be unaware of too high driving speeds and might find themselves in a risky situation.

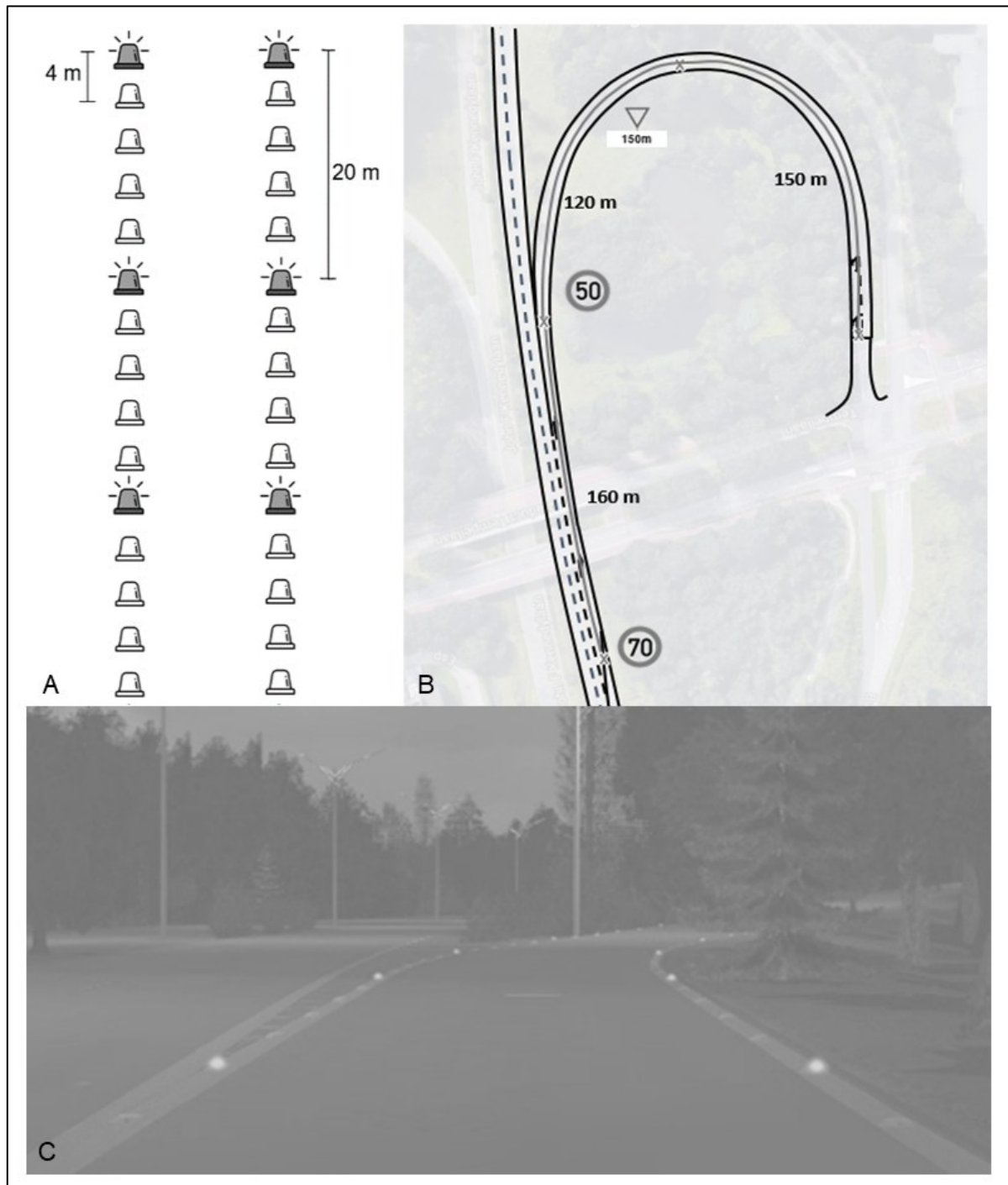
The optic flow paradigm describes that drivers perceive their movement relative to the environment (e.g., Feria et al., 2003; Gibson, 1950; Higuchi et al., 2020; Palmisano, 2002; Pretto & Chatziastros, 2006). In Study I, we chose an intervention consisting of light spots embedded on both sides of the road to support drivers in adapting a safer driving speed. This was an achievable solution to test the effect of a visual intervention not only in the driving simulator but also in naturalistic traffic within a reasonable timeframe that would enable our findings to be relevant for further development of interventions to mitigate too high driving speeds (see also Köhler et al., 2019). The light stimuli were placed every 4 m (driving simulator study) or every 6 m (field test) with every fifth light turning on (see Figure 3). They either activated right in front of the targeted car without further movement component or were animated in such a way to create the impression of moving towards the driver. The oncoming lights aimed at influencing the optic flow (e.g., Gibson, 1950) and distorting speed perception by giving drivers the impression of driving faster than they actually do. To see if the principle of lights on the side of the road worked, we chose red lights. Reacting to red lights with

caution is evolutionary rooted (Donald, 1988; Edworthy & Adams, 1996; Goldstein, 1942) and red lights have a warning character especially in the traffic context by attracting drivers' attention (Kahneman, 1973) and signaling them to stop or, at least, slow down (Lidwell et al., 2010).

Before applying the intervention in naturalistic traffic, we tested it in a static driving simulator. The testing location was a curved motorway exit in Eindhoven, Netherlands. We mirrored this traffic location in the driving simulator for comparability with the subsequent field test.

Figure 3

Arrangement of the visuo-spatial light stimuli in the driving simulator study (A), sketch of the motorway exit (B; drivers coming in from the bottom), and exemplary view of the simulated motorway exit from a position slightly before the 50 km/h-sign with activated (red) lights (C). Taken from Köhler et al. (2022, p. 442).



We measured driving speed at stimulus onset, that is, the moment where the intervention was activated for participants at the beginning of the exit lane, and four seconds after stimulus onset, since this would be a timeframe in which a reaction of a driver would likely have occurred (e.g., Gates et al., 2007). The two light conditions *static lights* and *oncoming lights* were compared to a baseline without light stimuli. In the simulator study, participants were instructed to drive 100 km/h, which was higher than the allowed speed at this location, and to adjust their speed when they felt the need to. They also executed a secondary task (SuRT, Mattes & Hallén, 2009) to mirror workload during driving in regular traffic and were told to stop this before taking the motorway exit, which was where the light stimuli were then displayed.

While the study in the static driving simulator was a controlled experiment with recruited participants and the lights were shown to all participants, the study in naturalistic traffic was executed as a quasi-experiment with random and anonymous drivers for data protection reasons. Drivers were unaware of participating in a study. Data was therefore collected in a between-subjects design. In the field test, thermal cameras detected all vehicles entering the motorway exit and computer vision algorithms (for technical details see Berghaus et al., 2020; Berghaus et al., 2024) identified cars exceeding the speed limit (70 km/h at the beginning of the exit lane and 50 km/h at the beginning of the curve of the motorway exit) by more than 10 % and displayed the light spots only to those drivers exceeding this threshold to control for the previously mentioned habituation effects (Hautzinger et al., 2011).

In both studies, participants drove slower at 4 seconds after stimulus onset, likely moderated by the curve of the motorway exit. We did not observe a difference in driving speed in response to static light stimuli in the driving simulator study, but a first indication that oncoming lights could lead to the intended reduction of driving speed in line with the optic flow paradigm (e.g., Gibson, 1950) and other interventions distorting visual information in the driving context (e.g., Gates et al., 2008; Thaler & Sunstein, 2008). This could suggest that the merely visual information in the static driving simulator was not enough for drivers to get an ecologically valid feeling of their driving speed. Other studies on speed adaptation were often conducted in naturalistic driving settings (e.g., Gates et al., 2008; Thaler & Sunstein, 2008), which provided, for example, more sensory information. Further, our participants might simply not have seen the need to react to the stimuli by lowering their driving speed, potentially because they did not think that their driving speed could be critical.

The field test, however, revealed that drivers in both light conditions reduced their speed in response to the light stimuli, compared to the baseline. However, we did not find a

difference in mean driving speed between static and oncoming lights. It therefore remained unclear from Study I why drivers reduced their driving speed and if a general warning character of the lights (e.g., Kahneman, 1973), an influence on the optic flow (e.g., Gibson, 1950), or other factors such as driving experience or situational factors (e.g., Iftikhar et al., 2020; see chapter 1.2) could have had an influence as well.

To understand underlying mechanisms, we studied the influence of visual stimuli on speed perception instead of speed adaptation in Köhler et al. (2023). This aimed at aiding the development of interventions against speeding and is described in the following chapter 2.2.

2.2 Study II: Influence of Visuospatial Stimuli on Speed Perception

After the findings of Study I (Köhler et al., 2022; see chapter 2.1) illustrated that adding visuo-spatial stimuli in the form of lights on the roadside to the driving environment could generally lead to lower driving speeds, an explanation why the principle seemed to work on a perceptual level remained open. In Study I, the static lights had been designed with a general warning character in mind (e.g., Kahneman, 1973), while we hypothesized the oncoming lights to influence the optic flow (e.g., Gibson, 1950). We had expected both solutions to reduce driving speed, but a greater influence of the optic flow-based intervention.

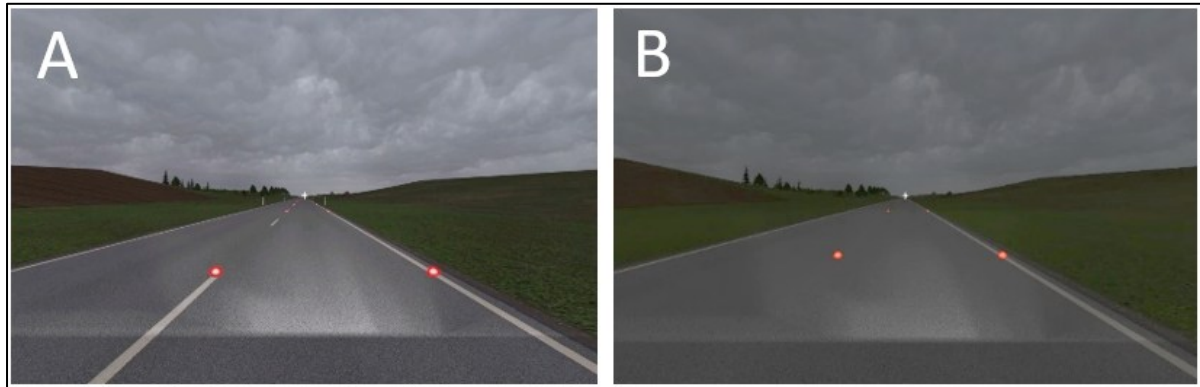
Adding stimuli to the driving environment to facilitate safer traffic behavior including lower driving speeds is in line with the concept of self-explaining roads or the Safe System Approach (see chapters 1 & 1.2.1; Theeuwes, 2021; World Health Organization, 2017, 2023b). But with the variety of information that needs to be integrated while driving (see chapter 1.1), relevant information could be overlooked (Theeuwes, 2021). To facilitate processing of relevant information, we need to understand how sensory information influences speed perception. Since we identified speed control of a vehicle as a spatial control task (see chapter 1.3; e.g., Köhler et al., 2022; Papakostopoulos et al., 2017) and that drivers in Study I (Köhler et al., 2022, chapter 2.1) indeed reduced their speed when encountering the light stimuli, the intervention tested in Study I to reduce driving speed provided a promising approach.

In Study II (Köhler et al., 2023), we investigated this further and applied the method of constant stimuli (Laming & Laming, 1992; Pretto et al., 2012) by using short video sequences of a drive in the driving simulator on a straight rural road, either with lane markings and reflector posts (Experiment 1A) or without (Experiment 1B). In line with Study I (chapter 2.1), these showed either static lights or oncoming lights during seven (Experiment 1A) or five (Experiment 1B) different traveling speeds scattered around 100 km/h (which was the

driving speed in a reference sequence without lights) in 10 km/h steps. Figure 4 shows screenshots from the video sequences.

Figure 4

Exemplary screenshot of video sequences with red light stimuli and difference in road specifications between Experiment 1A and Experiment 1B of Study II. Taken from Köhler et al. (2023, p. 5).

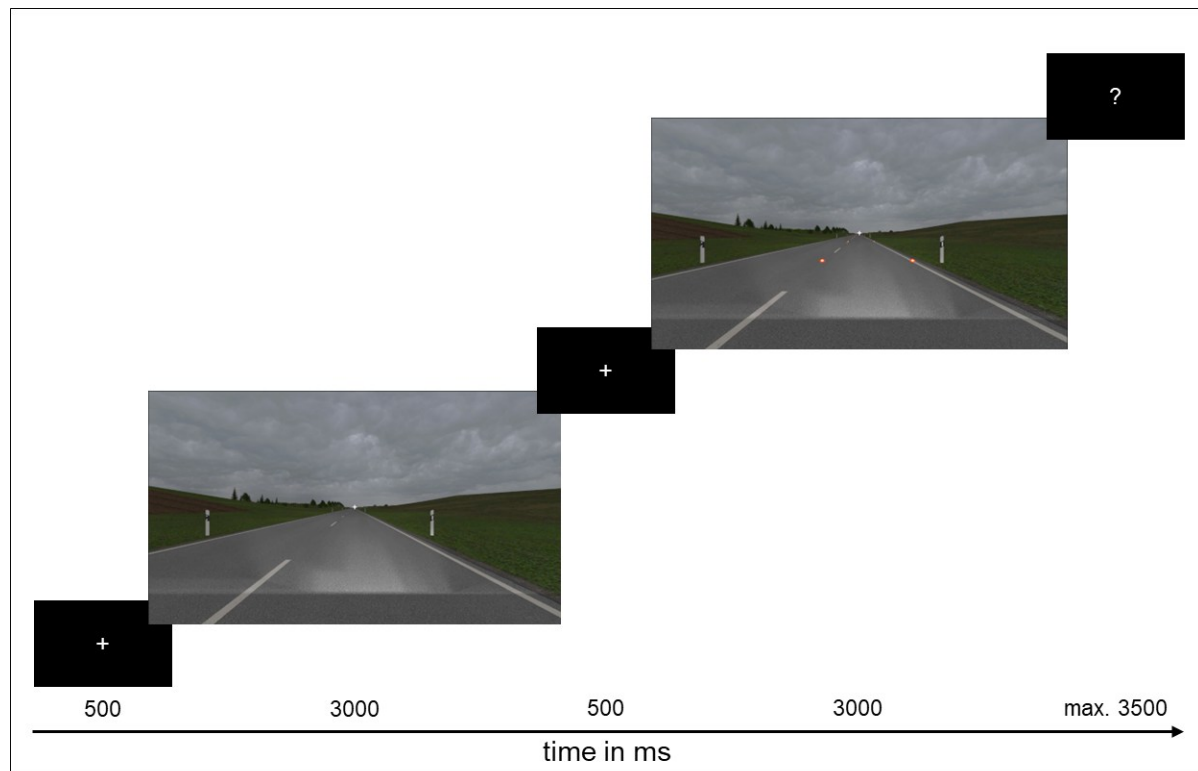


Note: Participants saw video sequences with red light stimuli on the roadside every 6 m that either remained static or were animated in a way to appear to be moving towards the driver. On the left (A): screenshot of the visual impression of Experiment 1A with reflector posts and road markings. On the right (B): screenshot of the visual impression of Experiment 1B without reflector posts and road markings.

To apply the method of constant stimuli, participants in a between-subjects design saw two consecutive video sequences in each trial, a test sequence in one of the traveling speeds and a reference sequence. The task was to decide with a key press in which video they perceived the traveling speed as faster. Figure 5 illustrates the test sequence. They experienced all traveling speeds several times. Their dichotomous key-press led to a binary logistic regression for every light condition and for every participant, culminating in the calculation of the point of subjective equality (PSE), which is the .5 probability point at which the driving speeds of two video sequences are perceived as the same by the participant and the likelihood to choose either option is equal (Kim et al., 2014). The lower the PSE, the higher the perceived traveling speed. This way, we could measure if participants perceived the traveling speed differently in response to the addition of static and oncoming lights to the driving environment. We found that some participants in Experiment 1A, which included lane markings and reflector posts, had counted these (see also Lidestam et al., 2019) against test instructions. We therefore conducted Experiment 1B without these.

Figure 5

Trial Sequence of Study II with exemplary stimulus material of Experiment 1A, taken from Köhler et al. (2023, p. 7).



Note: Illustration of the trial sequence with 500 ms of a black screen displaying a fixation cross, followed by a 3000 ms-long video sequence (reference sequence or test sequence, depending on the randomization), a 500 ms-long inter-stimulus interval, followed by another 3000 ms-long video sequence (reference sequence or test sequence, depending on the randomization), and a black screen with a question mark to indicate participants to respond, displayed for a maximum duration of 3500 ms. Video sequences in this figure show material from Experiment 1A.

When reflector posts and lane markings were present, the study did not reveal a difference between static and oncoming lights. This was likely because the task-irrelevant (visual) stimuli competed for the same resources (i.e., visual working memory) as the (visual) light stimuli (see also Wickens, 2008) and the active process of counting presumably prevented processing of the light stimuli (Cavanagh, 1992; Lidestam et al., 2019). In Experiment 1B without the task-irrelevant stimuli, however, we found that participants perceived the traveling speed in the video sequences considerably faster with oncoming lights than with static lights. This suggests that optic-flow based visual stimuli in the driving environment indeed influenced speed perception in our study, but only in the absence of stimuli fostering active processes.

In practice, drivers' speed perception can be influenced by an intervention aiming at the optic flow as described in this dissertation, that is, speed was perceived as faster with on-coming stimuli. Furthermore, speed-related visuo-spatial information can also be categorized into rhythm-based and energy-based processing, with rhythm-based processing being more dominant (Lidestam et al., 2019). While passing reflector posts and lane markings follows a distinct rhythm and is also being taught in driving lessons to estimate distances (Lidestam et al., 2019), energy-based processing in our case comes from the movement of the vehicle itself.

However, crosstalk phenomena limit human information processing, especially when cognitive processes interfere (Koch et al., 2018). So, when additional visual stimuli for speed estimation (such as reflector posts) are available, drivers are more likely to focus on these and have limited capacity for further information. The modality appropriateness hypothesis states that stimuli in the different perceptual modalities are processed in corresponding dimensions (Welch & Warren, 1980). This suggests that visual stimuli, as we investigated in Study I (chapter 2.1) and this Study II, can influence how we move in the spatial dimension while driving, that is, adjust our driving speed when it comes to longitudinal tracking. On the other hand, auditory stimuli attract attention more quickly than visual stimuli (see Aschersleben & Bertelson, 2003; Lukas et al., 2010; Lukas et al., 2014). Therefore, we investigated the role of corresponding auditory information to the visual light stimuli and in how far there might be an acoustic flow similar to the optic flow (Pretto & Chatziastros, 2006) in speed perception. I describe this in Study III (chapter 2.3).

2.3 Study III: Influence of Corresponding Visuospatial and Auditory Stimuli on Speed Perception

The results of Study II suggested that visuo-spatial stimuli in the form of lights embedded on the roadside affected speed perception of participants, but only in the absence of further visual stimuli. In addition to visual stimuli, auditory stimuli provide important information for speed perception (see chapter 1.3), especially because visual stimuli form only one source of information in driving (even though the likely most important source of information; Macadam, 2003) and might be insufficient if used isolated (Papakostopoulos et al., 2017). Auditory stimuli could limit processing of visual information when both sources of information were in conflict (see chapter 1.3; e.g., Morein-Zamir et al., 2003) but enhanced visual information when both modalities corresponded (see chapter 1.3; e.g., Ramkhalawansingh et al., 2016), especially in comparison to unimodal visual stimuli (Diederich & Colonius,

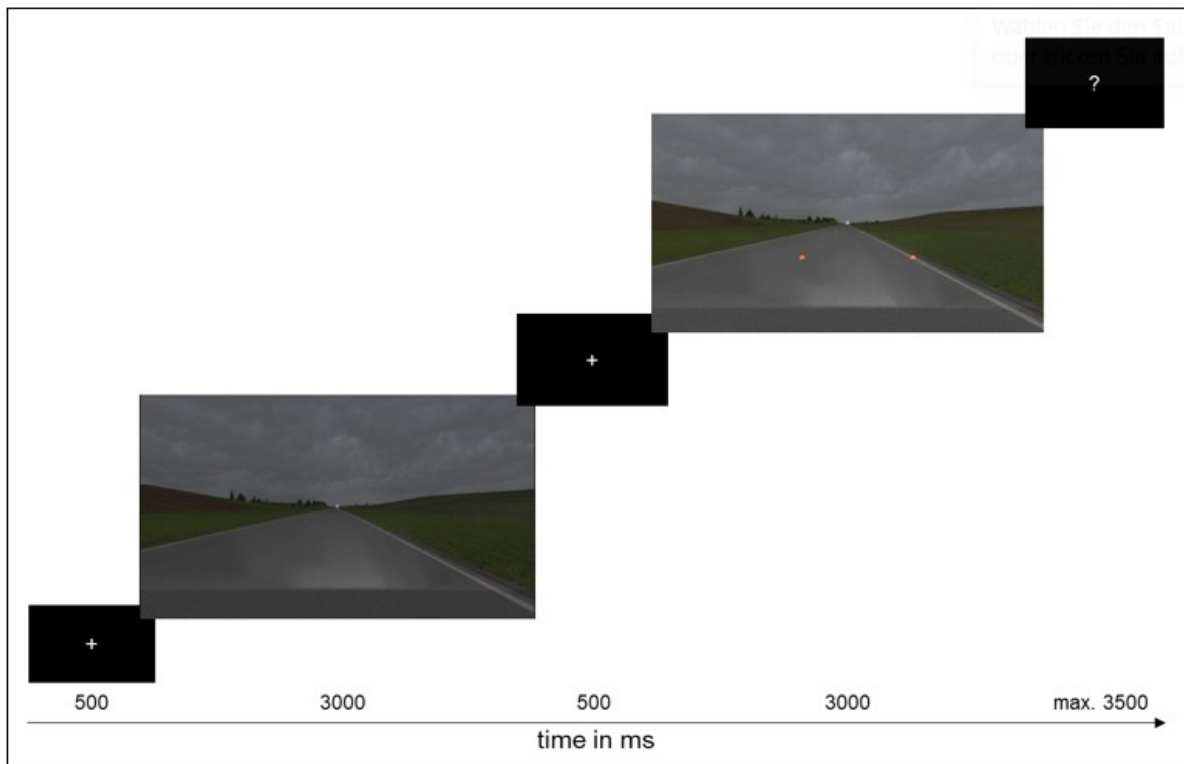
2004; Stefanics et al., 2005). It is therefore likely that corresponding auditory information, for example in the form of wind noise (Denjean et al., 2012, Fischer et al., 2012) could enhance visual optic flow-related information and create an acoustic flow in addition to the optic flow (Pretto & Chatziastros, 2006). More precisely, appropriate auditory information even intensified the effect ofvection, or the illusion of self-motion (Gagliano, 2016; Keshavarz et al., 2014).

We therefore investigated the influence of corresponding auditory information in Study III (Köhler et al., 2025) in two experiments in a between-subjects design. For this, we built on Experiment 1B of Study II (chapter 2.2, Köhler et al., 2023), where we compared the influence of static and oncoming lights on speed perception without any lane markings and reflector posts. As in Study II, we applied the method of constant stimuli (Laming & Laming, 1992; Pretto et al., 2012) with the PSE as dependent variable, again comparing sequences with five different driving speeds between 60 km/h and 120 km/h against a reference sequence of a drive on a simulated rural road at 100 km/h. Participants indicated via keypress which one of two sequences they perceived as faster for each trial. Participants encountered either unimodal visual stimuli (unimodal-vis), with the same light stimuli every 6m on the asphalt as in Study II, or bimodal visual-auditory stimuli (bimodal-vis+aud). These were the same lights enhanced with corresponding wind noise every time a light was passed. We also added an auditory-only manipulation check to test the effect of the auditory stimuli without any visual information, even though this has limited applicability in real traffic situations.

Figure 6 illustrates the trial sequence for Study III, which followed the same principle as in Study II. The auditory stimuli in all conditions with auditory information consisted of wind noise that sounded like overlaid air resistance noise to the visual stimuli. We tested this in two experiments that differed in the unimodal-vis condition. This did not contain engine sound in Experiment 1A (of Study III) to be comparable to Study II (chapter 2.2; Köhler et al., 2023). In Experiment 1B (of Study III), however, we added engine sound to the unimodal-vis condition to control for potentially confounding effects of the engine sound, because engine sound was always part of the bimodal-vis+aud condition and the unimodal-aud manipulation check. This change in Experiment 1B allowed us to isolate a potential effect of the auditory stimuli in the form of corresponding wind noise.

Figure 6

Exemplary trial sequence for unimodal-vis trials in Study III. Auditory information was added to the stimulus material of unimodal-vis trials for the bimodal-vis+aud trials (not displayed). Taken from Köhler et al. (2025, p. 7).



Note. Illustrations of the trial sequence with 500 ms of a black screen displaying a fixation cross, followed by either the video sequence (reference sequence or test sequence, depending on the randomization) with (bimodal-vis+aud) or without (unimodal-vis) auditory information or only auditory information for unimodal-aud. This was followed by a 500 ms-long inter-stimulus interval, followed by another video or auditory sequence (reference sequence or test sequence, depending on the randomization), and a black screen with a question mark to indicate participants to respond.

In line with Study II (chapter 2.2; Köhler et al., 2023), we found that traveling speed was perceived as faster in conditions with oncoming stimuli compared to static stimuli. The optic flow (Gibson, 1950) and, in the case of bimodal stimulus presentation, combined optic and acoustic flow (Pretto & Chatziastros, 2006) therefore likely influenced the speed perception of our participants. More precisely, results did not only reveal the influence of oncoming lights on speed perception for unimodal visual stimuli as in Köhler et al. (2023) and thus replicated this finding of Study II, results of Study III also revealed that this effect was more than twice as large with added corresponding wind noise during bimodal-vis+aud stimulus presentation. Previous studies therefore underestimated the influence of oncoming stimuli on

speed perception. The corresponding auditory information likely reinforced the visual information (temporal ventriloquism, Gagliano, 2016; Keshavarz et al., 2014; Ramkhalawansingh et al., 2016). The development of countermeasures against speeding that build on optic and acoustic flow related information should therefore consider bimodal stimulus presentation.

While results of Experiment 1A specifically for oncoming stimuli revealed an only numerically but not significantly lower PSE for bimodal-vis+aud stimuli compared to unimodal-vis stimuli, the PSE for bimodal-vis+aud Stimuli in Experiment 1B was significantly lower than for unimodal-vis stimuli. The difference between unimodal-vis conditions of both experiments was the missing engine sound in the unimodal-vis condition of Experiment 1A. However, the results of the post-hoc analysis did not suggest that engine sound should have influenced our results. However, since the influence of oncoming stimuli on speed perception was lower in Experiment 1B also in the identical bimodal-vis+aud conditions of both experiments, this can likely be attributed to a random sampling effect and should be monitored in future studies.

Interestingly, the auditory information alone in our manipulation check showed the same influence of higher perceived traveling speed when encountering oncoming auditory stimuli compared to static auditory stimuli on speed perception. This effect, especially in the absence of visual information as the presumably most important source of information in driving (e.g., Köhler et al., 2023), underlines the important role of auditory information in speed perception (in line with Horswill & Plooy, 2008).

3 Empirical Conclusion and Future Research

In this dissertation, three studies were conducted to investigate the influence of visual and auditory stimuli on speed perception and speed adaptation. The findings can aid in the development of interventions to reduce driving speed (as a major risk factor in traffic, see chapter 1). Results of Study I (chapter 2.1) showed that drivers in naturalistic traffic reduced their driving speed in response to the light stimuli, regardless of whether they were animated in a way to create the impression to move towards drivers (oncoming lights) or remained static. While Study I focused on speed adaptation when participants encountered the experimental stimuli, Study II (chapter 2.2) focused on speed perception of the same stimuli in a laboratory setting. Two experiments revealed that speed was perceived as higher when participants saw oncoming lights compared to static lights, but only in the absence of additional visual stimuli like reflector posts and lane markings that a speed estimation could be based on, as well as active processes such as counting stimuli. The final Study III (chapter 2.3) investigated the influence of auditory stimuli corresponding with the simultaneously presented light stimuli on speed perception. Results showed a replication of the finding of higher perceived speed for oncoming stimuli compared to static stimuli from Study II. This effect, however, was considerably stronger with corresponding wind noise, suggesting that previous studies underestimated the potential of oncoming stimuli on speed perception. Therefore, auditory stimuli not only influenced speed perception per se, but also reinforced visual information when presented correspondingly.

In the following chapter 3.1, I will discuss the results of this dissertation in relation to further research in this field. Chapter 3.2 describes potential for future research, while the final chapter 3.3 provides an overall conclusion.

3.1 Empirical Conclusions Regarding Human Speed Perception

All in all, the results of the empirical studies showed that speed was perceived as faster in conditions with oncoming stimuli than in conditions with static stimuli, but only in the absence of additional visual stimuli that might influence speed perception similarly to the experimental stimuli. This suggests that stimuli based on the optic flow (Gibson, 1950) and combined optic and acoustic flow (Pretto & Chatziastros, 2006) generally influenced speed perception. In the following, I will first present the empirical conclusions regarding visual stimuli and build on this to deduct conclusions regarding corresponding bimodal stimulus presentation.

On the one hand, oncoming visual stimuli influenced speed perception in Study II and Study III, but, on the other hand, showed no difference to static visual stimuli when assessing speed adaptation in Study I. It is therefore unlikely that the oncoming lights in Study I influenced the optic flow *per se*, even though we found an indication for a potential influence of oncoming lights on speed adaptation. This is, however, in line with the result of Study II that oncoming lights influenced speed perception only in the absence of additional visual stimuli in the driving environment that a speed estimation could be based on and active processes like counting reflector posts. In active driving situations, drivers must execute many tasks in parallel and allocate their cognitive resources in a way to meet task demands (see chapter 1.1; e.g., Stapel et al., 2019). Participants in both the driving simulator study and the field test of Study I had to execute an active driving task. Especially the experimental task in the driving simulator was presumably very challenging for participants and might not have left room for processing further information, that is, the experimental stimuli. Driving actively is safety-related and drivers therefore likely prioritized the task of keeping themselves safe (see chapter 1.2; e.g., Papakostopoulos et al., 2017) by staying on the road in the challenging situation of the motorway exit in combination with the unfamiliar driving dynamics of the static driving simulator. Furthermore, the higher the cognitive load, the less likely drivers are to have the cognitive resources (i.e., working memory) for checking for further input that is not directly related to their current task (e.g., Lehtonen et al., 2012). In the driving simulator study, this consisted of following the road, executing a secondary task (SuRT, Mattes & Hallén, 2009), and taking the motorway exit. Due to the capacity-limitation of the human information-processing system (Kahneman, 1973), further visual information such as the visual stimuli in Study I could presumably not be processed fully because these competed for the same cognitive resources (i.e., visual working memory, see chapter 1.1; Wickens, 2008). However, any light stimuli in Study I led to lower driving speeds, so the lights in general influenced speed adaptation. They likely served as a warning mechanism (e.g., Edworthy & Adams, 1996), suggesting that they did not influence the optic flow. Therefore, the lights in general might have had an influence on driving speed, but not the movement component of the oncoming lights.

The results regarding visual stimuli from Study II suggest that additional visual information in the driving environment indeed influenced speed perception, but only when participants were not distracted by stimuli in the same modality or occupied by other processes. So especially in very busy traffic situations, drivers might just not be able to process additional speed-related information. When designing interventions against speeding, the scope of

application needs to be considered. Such interventions can only be effective if drivers are not too distracted by other tasks, for example by demanding traffic situations. This could be especially possible for interventions in the infrastructure, because these target all drivers at one location. For interventions in vehicles on the other hand, likely in the form of Advanced Driver Assistance Systems (ADAS), developers need to take the circumstances in which they plan to apply interventions into account. It is possible that drivers do not have the cognitive capacity to process provided information. It could, for example, either be necessary to display information repeatedly or to use driver state monitoring and only display interventions when workload is comparably low and the likelihood is high that drivers might be able to process an intervention (e.g., Peruzzini et al., 2019; Sriranga et al., 2023). It should also be noted that not only information regarding safer driving speed could be overlooked, but also that drivers could ignore other safety critical information that is displayed in the same modality as the intervention targeting speeding. So, while the driving speed might not have been too critical yet, another aspect could have been critical, for example, a cyclist in the way of driving.

The finding of this dissertation that drivers might not be able to process (or even ignore) visual interventions if they are distracted by other stimuli or occupied with other tasks brings up another aspect: While results did not show an influence of visual stimuli on perceived speed in the presence of other (visual) stimuli that are relevant for estimating speed or active processes in the form of counting reflector posts, auditory stimuli attract information more quickly than visual stimuli (see chapter 1.3; e.g., Aschersleben & Bertelson, 2003; Lukas et al., 2014). In some situations, it could be helpful to attract the attention of drivers with auditory stimuli and use this advantage in the design of interventions mitigating speeding. Further, even information that is not relevant for a current task can influence performance, as explained by so-called congruency effects. In a spatial task under laboratory conditions, Lukas et al. (2010) investigated crossmodal selective attention. Even if incongruent information was irrelevant for a response in the target modality, that is, the modality that participants were asked to pay attention to, it was still processed to a certain degree. Related to the example of potentially not processing interventions in the driving context mentioned in the beginning, this could mean that any intervention against inappropriate speed is likely processed to some degree, especially because salient stimuli capture attention (e.g., Lange-Malecki & Treue, 2012). How much this might be processed remains open at this point of this dissertation.

Nevertheless, auditory information can reinforce visual information when the two sources of information correspond (see chapter 1.3; e.g., Gagliano, 2016; Keshavarz et al., 2014), and this is exactly what we found in Study III of this dissertation: When the light

stimuli and the overlaid wind noise were displayed simultaneously, speed was perceived as even faster, suggesting that bimodal stimulus presentation had an advantage over unimodal visual stimulus presentation also in the driving context. This even suggests that studies with unimodal stimuli, as Study I and Study II of this dissertation, considerably underestimated the influence of oncoming stimuli on speed perception. Applied to the development of interventions against speeding, this is a clear indication that developers need to take different perceptual modalities into account and consider especially the combination of corresponding visual and auditory information. While it would be straightforward to develop an intervention based on visual information, enriching the information with a corresponding auditory component holds great potential to lead to more effective interventions. Similar to a car's traffic sign recognition when entering a low-speed zone and still having a higher driving speed, the car would emit a warning sound and display the warning (warning drivers about, e.g., exceeding the speed limit has become a mandatory functionality for new vehicles introduced on the market since July 2024, Regulation (EU) 2019/2144). Here, however, driver attention is drawn to the visual information by the auditory warning, but the visual and auditory warning do not correspond, they are different levels of information. Displaying the same kind of information across different modalities as in Study III could lead to an even higher advantage for traffic safety, since irrelevant or even incongruent information for speed perception would not impact the response (see Kreutzfeldt, 2017, for an overview on modality-specific influences on cognitive control). This would make use of the ventriloquism effect, where auditory stimuli seem to come from visual stimuli if the two stimuli correspond (e.g., Recanzone, 2003).

Furthermore, the findings regarding unimodal auditory stimuli were particularly interesting: Not only did the corresponding auditory information significantly reinforce the visual information, but unimodal auditory stimuli alone influenced speed perception. This is notable, because driving is not possible without visual information and has also been defined as a spatial control task before (see chapter 1.3; Köhler et al., 2022), relying on visual input. The unimodal auditory condition therefore held limited external validity. Nevertheless, even though vision as the primary source of information in driving (e.g., Macadam, 2003) was not present, traveling speed could be perceived as faster or slower compared to other sequences and oncoming auditory stimuli had an influence on perceived speed. This again highlights the potential of auditory information in the development of interventions against speeding. However, the relevant input modality for the final action execution in driving is still the visual modality. Lukas et al. (2010) found a visual dominance effect indicated by better performance when reacting to visual stimuli compared to auditory stimuli in spatial tasks. Results by

Kreutzfeldt (2017) suggested that the benefit of visual information in spatial tasks depends on the task requirements: visual stimuli had an attentional benefit over auditory stimuli in direct spatial tasks, but this was reduced when the response to stimuli involved a translational stage, for example, verbal. It therefore remains open whether auditory stimuli changed only speed perception or would even lead to a changed speed adaptation when participants would drive themselves. I discuss this and other aspects further in the following section on future research.

3.2 Potential for Future Research

The results of this dissertation also lead to potential for future research to gain an even deeper understanding of not only perceptual mechanisms and their application in the traffic context, but also regarding the development and testing of concrete interventions against inappropriate speed as a severe risk for traffic safety. Furthermore, there are some limitations to the results and resulting considerations for further research that I discuss in the following.

3.2.1 Research on Perceptual Aspects

In this dissertation, I explored the role of visual stimuli in speed perception with and without additional visual stimuli potentially influencing speed perception, and then focused on bimodal stimulus presentation, again without additional visual stimuli. The influence of corresponding bimodal visual and auditory stimuli on speed perception was therefore not tested with competing visual stimuli (that might also be relevant for speed perception other than the experimental stimuli on the road). However, bimodal stimulus presentation as tested in Study III could potentially lead to improved processing of the speed-related information provided by the intervention, even with additional (visual) stimuli that a speed estimation could be based on, and especially since auditory information captures information more quickly than visual stimuli do (see chapter 1.3 & chapter 3.1; e.g., Lukas et al., 2014) and might therefore lead to improved processing of (optic- & acoustic) flow-related information (Pretto & Chatziastros, 2006). Auditory information attracts attention more quickly than visual information (see chapter 1.3; e.g., Lukas et al., 2014). This could draw attention from other tasks to the stimuli aiming at influencing the optic flow. Going in a similar direction, it could be worthwhile to investigate if perception of driving speed can be influenced in a linear way. More precisely, if (especially bimodal) stimuli with a higher sense of urgency would lead to an even higher perceived speed, for example, faster movement of stimuli towards drivers.

The conducted studies showed a variety of different stimuli other than the stimuli that were part of the experimental manipulation, that is, the road itself including road markings and reflector posts, the surroundings of the road including grass, or the sky. All of these were moving pixels in a video sequence of a simulated drive, except for the field test in Study I. Most of these stimuli moved in a similar way across the different video sequences with varying driving speeds and are therefore unlikely to have led to any difference in perceived speed. We have added a small percentage of pixels in relation to the overall pixels available in each video as part of the experimental manipulation, more precisely in the form of oncoming or static lights. If raising the results to this abstract level, it becomes clear that these few experimental stimuli were obviously able to influence human judgment (binary, in the case of the described studies), despite their under-representation and incongruence (especially in the case of oncoming lights) to the other stimuli that make up the rest of the video sequence. The key here seems to be stimulus salience, indicating that salient stimuli capture automatic attention even if nominally irrelevant (see Köhler et al., 2023; Lange-Malecki & Treue, 2012). Therefore, stimuli aiming at influencing driving speed need to capture automatic attention to be able to influence speed perception and for their processing to not be overruled by the processing of other stimuli. Future research could determine which level of stimulus salience is needed or even sufficient to influence speed perception. Different specifications of the stimuli and their salience might lead to other results, for example by placing the lights at a higher level or by choosing different auditory stimuli.

The question remains if there could be further stimuli that might capture automatic attention other than the tested stimuli. Stimuli that might be unexpected for drivers could also be relatively salient, since objects with high contrast (light stimuli in the case of the reported studies) or sudden movements increase stimulus salience. The SEEV model on visual scanning behavior calculates, for example, how drivers allocate visual attention based on stimulus salience (affected by attention capture), effort needed to switch attention to a new location, expectancy as frequency of informational change (e.g., a blinking light or a weirdly moving vehicle), and value, which is the task-relevance of a stimulus (Horrey et al., 2006, for an overview see Gugerty, 2011). So even transverse-bar road markings influenced speed perception and speed adaptation (see chapter 1.2.2; e.g., Thaler & Sunstein, 2008), presumably especially when they were unexpected. Potentially, the additional visual stimuli (i.e., road markings and reflector posts) in Study II had a salience that was high enough to capture participant's attention, leading to no advantage of the tested oncoming light stimuli over static light stimuli. This leads to the potential impact of the stimuli tested in this dissertation: when

developing an intervention against speeding, it would be interesting to directly compare different stimuli in different modalities with the same methodologies and, thus, being able to directly quantify their likely advantage and where similar additional stimuli might capture attention as well.

To determine the role of the components of bimodal stimulus presentation further, it would be interesting to test auditory stimuli that do not correspond with the information of visual stimuli. This would allow us to isolate the effect of the two modalities more accurately. Developers of interventions against speeding might intend to focus on displaying interventions in one modality for economic reasons. In this case, deeper knowledge if speed adaptation could either be a spatial control task likely to benefit more from visual interventions, or a temporal control task likely benefiting more from auditory interventions could support this decision making. Auditory information has been found to limit processing of visual information when both sources of information were in conflict (see chapter 1.3; e.g., Morein-Zamir et al., 2003). Investigating the influence of auditory stimuli that do not correspond with the visual information could provide insights regarding visual dominance in speed perception. Since I determined speed control as a mainly spatial task in chapter 1.3, auditory information that does not correspond with visual information should technically not influence speed perception. However, as outlined in chapter 3.1, even incongruent information that is irrelevant for task execution is being processed (e.g., Lukas et al., 2010). We found a combined optic and auditory flow (Pretto & Chatziastros, 2006) for corresponding bimodal stimuli in Study III, suggesting that speed control is likely not only a purely spatial task relying on visual information (which is also in line with Horswill and Plooy, 2008). Even more so, combined visual and auditory information had a far greater influence on speed perception than visual information alone. In a study by Lukas et al. (2010), visual distractors interfered more with the processing of auditory information than vice versa. Findings by Kwon et al. (2009) showed that in this case of incongruent visual and auditory information, visual information influenced speed perception more. Future research should focus on the degree of this influence for the stimuli tested in this dissertation. In the same laboratory setting as Study II and Study III, this could be realized by, for example, presenting the audio track of the wind noise in a different driving speed than the video material of the light stimuli. This way, the resulting PSE (representing the perceived speed) would indicate if the perception of speed relies more on the auditory or on the visual information or if indeed the combined presentation of congruent information in the two modalities has the greatest influence on speed perception. This could support the design of future interventions against speeding by providing clear guidelines if the

targeted task is, as the results of this dissertation suggest, indeed a task that benefits most from combined visual and auditory stimuli, or if trade-offs could be accepted for economic reasons. This aspect leads to needed research for concrete development of interventions against speeding, which I outline in chapter 3.2.3. Before this, however, I outline the difference between laboratory conditions and studies in naturalistic traffic and the potential impact of the latter on the presented results.

3.2.2 *Laboratory Conditions vs. Naturalistic Traffic*

Note that Study II and Study III were conducted under laboratory conditions. This allowed a very controlled environment to isolate the effects of our experimental stimuli and allowed to deduct the perceptual mechanism of the tested stimuli. The controlled variables included very stable traffic conditions and elimination of potentially competing stimuli like either the reflector posts and road markings in Study II or other traffic participants. It remains open, however, how well these principles work in naturalistic traffic. We found that (oncoming and static) lights could slow down drivers in Study I especially in the field test in a naturalistic traffic scenario. While replicating the results from Study II and Study III in naturalistic traffic could be a promising approach, it should be noted that the field test of Study I already had a large sample and resulting high power. However, the setting of a motorway exit (that had been chosen for practical reasons, since the location allowed us to conduct a field test with structural modifications by implementing the lights into the road surface) was very artificial and might not represent general traffic situations well enough. A straight road could have led to more generally applicable results.

Future research should furthermore explore the influence of bimodal stimuli with corresponding visual and auditory information in a naturalistic driving setting, since the auditory information in Study III under laboratory conditions reinforced the visual information. This could potentially be tested by implementing both light stimuli and auditory stimuli at a traffic site or by implementing the setting inside a test vehicle via a head-up display and the vehicle's speakers. Driving speed in a study by Schütz et al. (2015) was underestimated not only when driving actively but also as a passenger, which could, to a certain degree, be comparable with our studies on (traveling) speed perception under laboratory conditions. The effect of constant underestimation of driving speed was relatively stable between artificial and real traffic situations (Schütz et al., 2015). This could be an indication for similar results when applying the results in naturalistic traffic scenarios, especially when these match the specifications of the laboratory studies. It furthermore underlines the relevance of the methodological

setup of Study II and Study III with regards to automated driving, where drivers (at least temporarily) become passengers with increased automation (see SAE International, 2021, for an overview over the levels of driving automation).

Testing the experimental stimuli in a static driving simulator led to different results than the field test and the subsequent laboratory studies. More specifically, results did not show an influence of neither static nor of oncoming light stimuli on speed adaptation but revealed this effect in the field test. Further, we found an effect of oncoming lights influencing speed perception in the studies under laboratory conditions. While laboratory studies have their own limitations in terms of applicability to the real world, they did provide valuable insights into the underlying mechanisms of speed perception. We expected participants in the simulator study to behave similarly to real traffic, but the setting was likely too artificial for them to behave naturally. Especially experiments targeting perceptual factors and slight responses to stimuli in different modalities might not be suited to test in such an environment (Köhler et al., 2022). At least a high-fidelity driving simulator could lead to more ecologically valid results. A similar limiting factor could also have been the stimulus salience in the driving simulator, since participants did not encounter real lights but rather an image of lights. Especially when it comes to examining perceptual factors in driving-related tasks, the way the stimuli were displayed in combination with the novel situation in the driving simulator might not have been enough for clear results. This should be considered for future research by either recruiting participants who are used to driving in a driving simulator (which can lead to further bias because they might not represent the “average” driver), training regular participants for a longer period of time before letting them encounter the actual experimental task, or switching to testing such scenarios on a test track, which can lead to other (financial) obstacles. Using augmented reality to overlay visual experimental stimuli over the real world could combine the advantages of testing on real roads in real vehicles with the relative cost efficiency of simulations, since no hardware needs to be built up on site.

3.2.3 Development of Interventions Against Speeding

The results of this dissertation provide valuable insights regarding human speed perception and aim at aiding the development of interventions against speeding, which target this perceptual level. How speed and, in the end, potential interventions are perceived has an influence on behavior. This in turn can influence traffic safety. In the case of the tested stimuli in this dissertation targeting the optic flow (Gibson, 1950), drivers would feel to be driving too fast for a traffic situation and decide to reduce their driving speed earlier than without

these stimuli. Future research in the development of interventions is needed to determine the degree of which these perceptual influences indeed impact speed selection.

Insights into the underlying perceptual influences are just one step in a (ongoing) development process. As the results from Study I suggest, the tested (light) stimuli were suitable for quasi-subliminal manipulation of speed adaptation (Köhler et al., 2022; Köhler et al., 2023). However, it is up to the individual driver if they indeed change their behavior in response to the intervention. The challenge in the design of interventions is therefore to conceptualize solutions that are relevant enough for drivers to change their behavior. In the case of the tested (visual) oncoming and static lights of this dissertation, these were presumably only relevant enough for drivers in the absence of additional visual stimuli. At the same time, implementing such interventions must not affect traffic safety because drivers might not have enough information-processing capacity left to safely operate their vehicle (see chapter 1.1; Kahneman, 1973). Hence, stimuli for application in naturalistic traffic need to be designed in a way to not draw attention away from safety-related tasks while driving. Future research on this is needed in the ongoing development process of appropriate interventions.

Further, testing the findings in varying settings could support in identifying situations in which different interventions targeting speeding drivers could be especially helpful. The research up to this point has mainly focused on deducting potential interventions first (for an overview, see Karlsson et al., 2017; Köhler et al., 2019) and testing them in one location. It could, however, be possible that some interventions work better in certain areas than others. So, while an auditory stimulus might, hypothetically speaking, work great at night without many additional noises on a rural road, the same intervention is unlikely to have the same effect in busy city traffic. A promising approach could be to test a potential intervention in different locations (e.g., rural setting, suburban setting, city traffic, and motorway; high vs. low traffic load) and scenarios (e.g., straight vs. curved roads, obstacle avoidance, lane changes, merging situations) before ruling them out. It could, for example, be worthwhile to test the effect of stimuli influencing the optic and/or acoustic flow not only in such a controlled setting as in most of the studies of this dissertation, but also, for example, in more congested traffic situations (e.g., Iftikhar et al., 2020) in naturalistic traffic. Considering such situations will have to lead to further considerations regarding applicability. This includes available capacity for information processing due to the complexity of a traffic situation, which, in the case of the stimuli tested in this dissertation, could point towards limited applicability in more busy situations. This also includes considerations regarding the underlying problem of a

traffic situation and if this really is inadequate speed or if another behavior of drivers would be more problematic like, for example, limited attention to a cyclist.

In addition to auditory stimuli influencing the acoustic flow, the influence of engine sound should be investigated: While missing engine sound did not influence our results in Study III, previous studies found that participants usually drove faster than the speed limit in the absence of engine sound (Denjean et al., 2012; Merat & Jamson, 2011). A potential field for further research could be how different levels of engine noise might influence speed perception. It may be more comfortable for drivers and passengers to hear less engine noise (e.g., Bijsterveld, 2010), but in the case of an intervention against speeding based on auditory information or a combination of visual and auditory information, potentially confounding effects of engine sound should be investigated.

3.3 Conclusion

In this dissertation, I researched the role of visual and auditory stimuli on speed perception while traveling in passenger cars. Three studies investigated the influence of static and oncoming stimuli on the optic and acoustic flow and, thus, the adaptation (Study I) and ultimately the perception (Study II & Study III) of speed. Taken together, oncoming visual stimuli led to higher perceived speed, but only in the absence of additional visual stimuli that could be perceived similarly to the experimental stimuli and active (cognitive) processes. This suggests that speed perception can be influenced by speed-related visual stimuli. Corresponding visual and auditory stimuli that created the impression of moving towards the participants led to considerably higher perceived speed than unimodal visual stimuli. Even unimodal auditory stimuli in the form of wind noise like passing an object had an influence on speed perception.

The findings of this thesis are relevant for the design of future interventions against speeding. When displaying speed-related interventions, developers need to ensure that drivers can process the information accordingly and are not too distracted by, for example, busy traffic situations. Furthermore, results suggest using corresponding bimodal (visual and auditory) stimuli in interventions targeting speed perception for a higher effectiveness than unimodal visual stimuli. While driving and especially speed control is a mainly visual task, suitable speed-related auditory information alone could lead to higher speed perception. Nevertheless, altered speed perception does not necessarily lead to adaptation of lower driving speeds. Hence, the effect of combined visual and auditory and unimodal-auditory stimuli on speed adaptation should be subject to future research. The same applies to the applicability of the

tested stimuli in naturalistic traffic and, hence, the actual development of realistic interventions against drivers adapting a speed that is too high for a given traffic situation.

Overall, the results of this thesis address the gap between basic and applied research for understanding the perceptual foundations of speed perception in traffic. These provide guidance for the development of specific interventions against speeding that go beyond currently available approaches and support the Vision Zero, ultimately leading to less accidents and fatalities on our roads.

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Scientific Publications

Study I

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Study II

Köhler, A.-L., Klatt, M., Koch, I., & Ladwig, S. (2023). Investigating the influence of visuospatial stimuli on driver's speed perception: A laboratory study. *Cognitive Research: Principles & Implications*, 8(1), 59. <https://doi.org/10.1186/s41235-023-00513-x>

Study III

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Guiding Drivers towards Safer Driving Speed: Exploiting Visual Dominance in Speed Adaptation

Anna-Lena Köhler¹ *, Iring Koch², and Stefan Ladwig¹

¹ Institute for Automotive Engineering (ika)
RWTH Aachen University
Aachen, Germany

² Institute for Psychology
RWTH Aachen University
Aachen, Germany

*anna-lena.koehler@rwth-aachen.de

Abstract

Inappropriate speed is a main cause of accidents. Drivers are often unaware of potential risks due to inadequate speed. To prevent dangerous situations, we need to understand perceptual factors influencing human speed perception. Due to the prominent role of vision in driving, we examined the effect of visuo-spatial stimuli on speed based on the optic flow. While developing an adaptive infrastructure measure to reduce speed, we conducted two consecutive studies, a driving simulator study and a field test to investigate findings further. In both studies, we placed lights on two sides of a highway exit and either illuminated them statically or activated them in a way that they appeared to be moving towards the driver. We expected drivers to slow down more when seeing static light stimuli compared to a baseline without lights. We also expected drivers to decrease speed more in conditions with oncoming lights compared to a baseline, and to static lights, due to distorted speed perception. The first study in a static driving simulator revealed no difference between conditions. In the field test, both static lights and lights moving towards the driver led to a speed reduction compared to a baseline but did not differ from one another. Lights in general led to lower driving speed, potentially due to their warning character, but we found no difference between the light conditions, suggesting that the effect might not be based on the optic flow. Future research should investigate the relationship between driven and perceived speed more closely.

Keywords: *speed reduction, infrastructure nudging, adaptive safety measures, traffic safety, optic flow*

1. Introduction

In 2018, 62 % of fatalities with cars occurred on inter-urban roads, including many single-vehicle accidents caused by a driver losing control of the vehicle (European Commission, 2020). One problematic unsafe driving behaviour is that drivers often adopt a speed that is inappropriate for given circumstances (Groeger & Grande, 1996). Errors amplify with increasing speed (Taylor et al., 2000) and the higher the driving speed before a crash, the more severe the outcomes (Arvin et al. 2019). There is a clear relationship between driving speed and the severity of accidents (Aarts & Van Schagen, 2006; Merlin et al., 2020). Consequently, driving too fast can lead to dangerous situations and even accidents (see Arvin et al., 2019), making speeding an issue for traffic safety. In addition, if the average speed on European roads were just 1 km/h lower, over 2200 deaths could be prevented, taking another step into the EU's Vision 0 for traffic safety (European Commission, Directorate-General for Mobility and Transport, 2020). However, drivers may not be aware that they drive at an inappropriate speed in certain situations (Groeger & Grande, 1996; Kuiken & Twisk, 2001). However, research on driver's sensory dynamics has been very limited (see e.g. Nash et al., 2016). To prevent situations in which drivers might be unaware of inappropriate speed and are driving too fast, there is a need to understand perceptual factors influencing human speed perception and how this might affect driving behaviour.

In summary, this paper takes a first step in examining the role of sensory information during the development and implementation of an adaptive measure to reduce speed in traffic in an applied setting.

The studies described in this paper were part of the H2020-project MeBeSafe. Within this research and innovation action project, we led the development of a solution to encourage drivers towards adopting a safer speed without forcing them to do so (e.g. by threatening negative consequences such as fines), called nudging. Nudging is an approach to subliminally stimulate humans to make a desired choice without prohibiting alternatives (Thaler & Sunstein, 2008). The project aimed at implementing and testing such a solution in a naturalistic traffic situation, which led to a pilot in the laboratory followed by a field test, as described in this paper. Within this project, a motorway exit in Eindhoven, Netherlands, was available for testing a solution to slow down speeding drivers in real traffic. At this location, drivers are usually coming in too fast without necessarily being aware of the upcoming curve, which gets narrower as it continues. Slowing drivers down at such a location provided the scope for our research.

In general, speed control, or longitudinal tracking, is one of the tasks that need to be integrated while driving (Papakostopoulos et al., 2017). Based on multiple resource theory (Wickens, 1981), we can divide the primary driving task into several sub-tasks (Papakostopoulos et al., 2017; Stapel et al., 2019), which have usually been studied independently from one another (Papakostopoulos et al., 2017). For successfully carrying out the driving task, however, drivers need to integrate different sensory information contributing to the perception of their surroundings and their action execution. Hence, while driving, multitasking and divided attention plays a crucial role. Because human information processing is generally capacity-limited, (Kahneman, 1973), problems with this multitask coordination may occur when drivers select a task-irrelevant source of information in selective processing (for an overview see Koch et al., 2018).

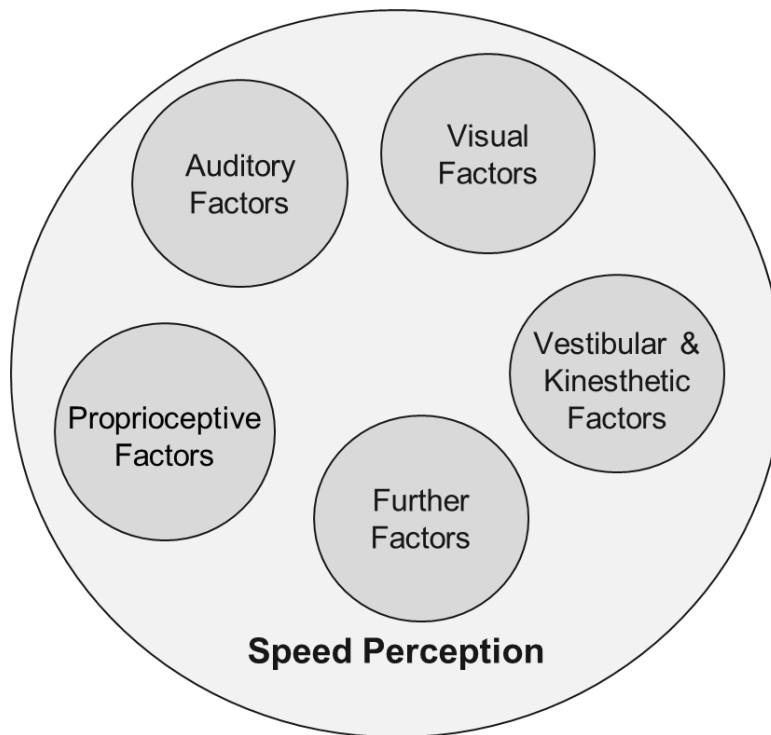
According to the modality appropriateness hypothesis (Welch & Warren, 1980), stimuli in different perceptual modalities are processed in certain dimensions, leading to the visual modality being linked to the spatial dimension (see also Lukas et al., 2014). While driving, a substantial amount of information is displayed via the visual channel. In this vein, humans perceive their own driving speed relative to the speed of the environment (Feria et al., 2003; Palmisano, 2002), which is in line with the optic flow paradigm (Gibson, 1950). Consequently, the faster objects pass by, the faster the perceived personal speed becomes. This has been shown by a series of experiments influencing the driving environment. On the one hand with lines whose distance to each other becomes smaller and smaller painted on the road surface (e.g. Thaler & Sunstein, 2008; Gates et al., 2008) or on tunnel walls (Manser & Hancock, 2007). On the other hand, Godley et al. (2004) manipulated lane width, where a lower width led to lower driving speeds. For an overview of different road markings targeting driving speed, please see Lee et al. (2013). Furthermore, it was also shown in the laboratory, where red- and cyan-coloured objects moved in a three-dimensional pattern on a white background and influenced the driver's own speed (*ego speed*) even more than two-dimensional information about self-motion (Palmisano, 2002). These findings based on visuo-spatial stimuli suggest that these are likely to influence driver's speed selection.

However, visual stimuli alone could likely be an insufficient source of information for drivers, which are to be complemented by drivers' hypotheses about the driving environment, potential hazards, and the behaviour of other road users, especially because of the high interaction between all perceptual cues and driver's expectations (Papakostopoulos et al., 2017). Therefore, segmenting and researching the most relevant individual components is crucial in understanding how speed is perceived and can potentially be influenced to lead towards safer

driving. Figure 1 illustrates perceptual factors that are likely to have an influence on speed perception, describing the percept *speed*.

Figure 1

Factors potentially contributing to speed perception.



Next to visual information and action effects that are often prioritized in research, other sensory information like vestibular or other proprioceptive input has been reported to contribute to the perception and control of self-motion (Kemeny & Panerai, 2003). This implies that other input modalities can play a role in speed perception as well. Correspondingly, a study by Reymond et al. (2001) reports vestibular and proprioceptive sensory channels to be significantly involved in driving tasks and to be especially relevant for the control of speed and steering. Visual information, however, is presumably the most important source of input while driving, while a great amount of information used by humans for control purposes has been reported to be retrieved from the vestibular and kinaesthetic channels, such as vibrations, steering wheel and pedals (Macadam, 2003), and haptic information described as the most direct form of motor information (Sigrist et al., 2013).

However, in line with the optic flow paradigm (Feria et al., 2003; Gibson, 1950; Palmisano, 2002) and the modality appropriateness hypothesis (Welch & Warren, 1980), Ward et al. (2000) reported vision to be more prominent in spatial localization tasks than e.g.

auditory information. Further, visual dominance describes an assumed advantage in processing visual input compared to other sensory input modalities (see e.g. Lukas et al., 2010; Lukas et al., 2014), depending on the task modality (see Kreutzfeldt et al., 2015). According to Gibson (1950) and Krüger et al. (1999), drivers are constantly monitoring both their own position and that of their vehicle in the driving environment. We therefore regard speed control of a vehicle as a spatial control task. This stresses the role of visual dominance, that is, if speed perception is indeed a spatial localization task. In this vein, this paper focuses on visual cues in speed perception.

Previous research has outlined possibilities to decrease driver's speed, i.e. by painting lines on the road surface whose distance to each other becomes smaller and smaller (Thaler & Sunstein, 2008; Gates et al., 2008), leading to lower driving speeds. To prevent habituation effects from continuously displayed measures such as painted lines (see Gates et al., 2008; Hautzinger et al., 2011), a dynamic solution could help: Light emitting spots can be activated only if a driver is detected to be driving too fast in a certain location. Therefore, this driver can be targeted directly and especially drivers taking a route frequently would not be as much at risk to develop habituation, potentially leading to a lower effectiveness of the solution. Having light spots equally spaced throughout the curved motorway exit available in our project would allow for turning the measure on and off at any position throughout the exit. Choosing stimuli appearing as lights likely leads to a higher salience of the visuo-spatial stimuli as compared to previously described experiments in this field of research (see e.g. Gates et al., 2008; Jamson et al., 2008; Palmisano, 2002).

In a study by Lehtonen et al. (2012) drivers approaching a curve typically focused on the occlusion point, which was defined as the closest point where the view of the road was blocked by an obstacle such as trees or other obstacles. Other publications reported e.g. the tangent point (e.g. Underwood et al., 1999) or other points ahead of them, which are in their direction of travel within 1-2 s (Lehtonen et al., 2013). In all cases however, the sides of the road are therefore likely in the periphery of the driver, which tended to be exposed to faster motions, according to Zhang et al. (2013), making it a suitable location for a solution influencing speed perception. Drivers usually try to maintain a central lane position (Michon, 1985). Cooper et al. (2013) reported that driving centrally on the road was even more pronounced when cognitive workload increased. We regard the task of leaving a motorway as a rather complex task, as a variety of information needs to be integrated at once, including not only speed control but also navigation tasks (Papakostopoulos et al., 2017). Therefore, neither

side of the road should be closer to the driver than the other, supporting displaying stimuli on both sides of the road.

We conducted an expert workshop to derive possible ideas to find a solution that can be activated and deactivated on demand to only influence drivers who are detected to be driving too fast. From several ideas (see Köhler et al., 2019), we chose visuo-spatial stimuli that either light up statically acting as a warning or that are creating an illusion of lights moving towards the driver. This was a solution that could target speed perception and was technologically feasible to develop until the field test (see Köhler et al., 2019).

Regarding the colour of the lights, there is little research examining the meaning of colours reliably to the author's best knowledge. However, Donald (1988), Edworthy & Adams (1996), and Goldstein (1942) described reacting cautiously to red lights as evolutionarily rooted. Furthermore, a publication by Kahneman (1973) suggests that red lights in traffic have a warning character and attract driver attention. This is in line with the robust rules in the colour scheme of traffic lights, signalling to stop at red, be cautious at yellow and to drive at green (see Lidwell et al., 2010). As red lights showed the potential to communicate a warning to slow down most clearly, especially considering the described traffic light analogy, we chose with a group of expert researchers in the field of traffic safety to test the effect of the adaptive light solution with red lights to provide drivers with a very clear communication strategy.

Nash et al. (2016) summarized that drivers usually reduce their speed to drive through curves. However, we expected drivers to adjust their speed even more when being presented with the light stimuli to be examined in this study. We expected different ways of displaying visuo-spatial light stimuli to have an effect on driving speed. Several studies suggest that humans are conditioned to respond to red lights with caution (see Donald, 1988; Edworthy & Adams, 1996; Griffith & Leonard, 1997). Therefore, we firstly expected drivers to react with adapting a lower velocity when we presented static lights compared to a baseline without light stimuli. Secondly, studies by Feria et al. (2003), Gibson (1950), Manser and Hancock (2007), and Palmisano (2002) suggest that drivers are likely to perceive their driving speed to be higher than it actually is when lights are moving towards them, due to the optic flow paradigm. Especially dynamic information could increase driver's perception of driving speed (Palmisano, 2002). Therefore, we expected drivers to react with adapting a lower velocity when moving lights were presented compared to a baseline without light stimuli. Thirdly, we regarded the movement component to have a greater influence on speed perception due to the optic flow paradigm (Feria et al., 2003; Gibson, 1950; Manser & Hancock, 2007; Palmisano

2002) then the static lights acting as a warning (in line with Kahneman, 1973). Therefore, we also expected drivers to react with adapting a lower velocity when lights were moving towards them, compared to static lights.

We examined mean driving speed at stimulus onset (t_0) and 4 s after stimulus onset (t_4) to see if visuo-spatial light stimuli might have an impact on the speed choice at a position close to stimulus onset, at which drivers could have already slowed down if they saw the need for it. It was difficult to determine an exact time at which we should see a first reaction of drivers in our study, as we did not expect drivers to stop but only to slow down (see Gates et al., 2007; Green, 2000; Summala, 2000) because, unless explicitly instructed, participants are unlikely to stop on the point, according to Summala (2000). We equated this to a yellow-light situation, in which a car is approaching a traffic light switching to yellow. When looking at first-to-stop vehicles in a number of cars approaching a yellow light, a study by Gates et al. (2007) found the probability to decide for a stop to be about 0.8 s when the travel time to the intersection was 4.5 s at the onset of the yellow light. This has some resemblance to our study. Applying this timeframe to our study, drivers were likely to have reacted to a stimulus, so that we could potentially already see that their reaction had led to a reduced velocity. Therefore, we assumed it would be likely that 4 s after stimulus onset, an effect in driving velocity could be observed if any of our experimental stimuli lead to a corresponding reaction.

To test our hypotheses, we first executed a driving simulator study at the Institute for Automotive Engineering (ika) of RWTH Aachen University, Germany (Study 1). Subsequently, we conducted a field test in natural traffic at the motorway exit in Eindhoven, Netherlands, which had been modelled in the driving simulator before (Study 2). These are reported individually in the following two sections, followed by a general discussion and conclusion.

2. Study 1: Simulator Study

We developed a driving simulator study setting to test different ways to influence human speed perception by simulated light stimuli at the side of the road. The light spots either remained static or included a movement component of the lights moving opposite to the driver's driving direction, thus giving the impression of moving towards the driver. We identified a motorway exit in Eindhoven, Netherlands, as a location with many vehicles speeding into a rather tight and tightening curve and modelled it in the driving simulator.

2.1 Method

2.1.1 Sample

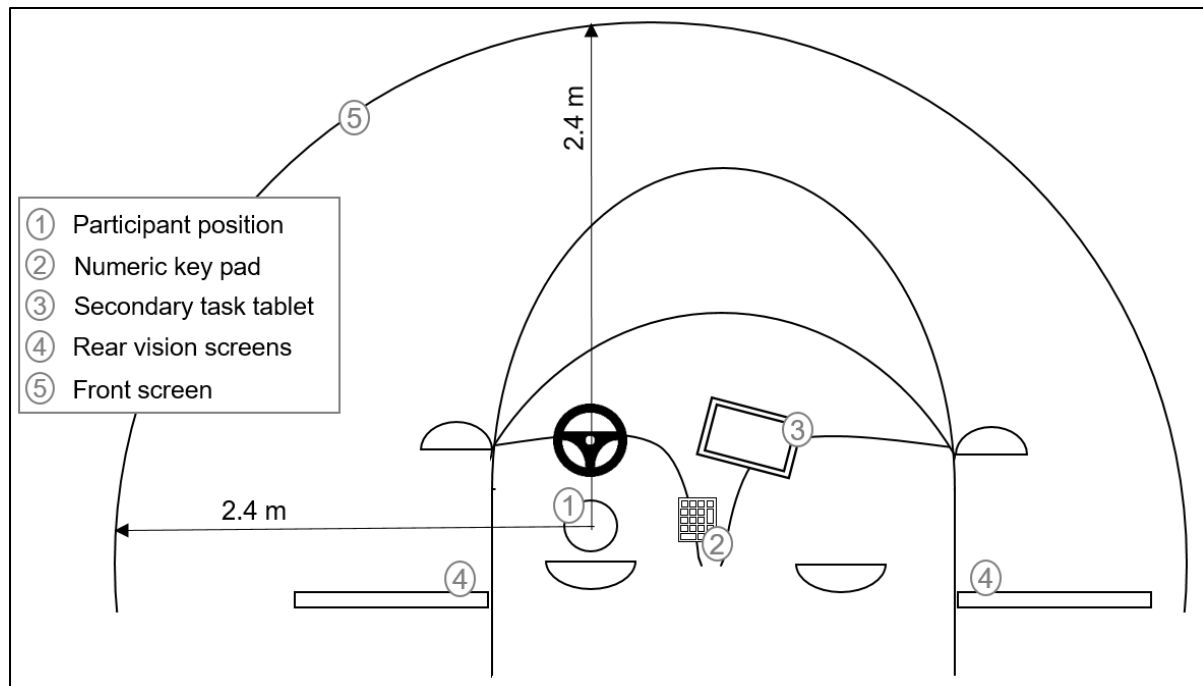
We used G*Power to estimate our sample size a priori and assumed, since there are no comparable simulator studies to our best knowledge, the following parameters for our within-subjects design with repeated measures (2 x 3): a correlation among repeated measures of .50 and an effect size of $f = 0.20$. We calculated that a sample size of 36 participants would allow to detect an effect of this size at $\alpha = .05$ with a power of .91 (see Faul et al., 2007). Considering dropout due to e.g. motion sickness symptoms, 54 participants recruited by a research panel took part in the simulator study in April 2018, 28 female and 26 male. All participants were naïve to the purpose of the experiment and received a monetary compensation of 25 €. All participants were fluent in German on mother-tongue level (C2), had normal or corrected-to-normal vision and no relevant colour vision defects. The mean age of the sample was 31 years ($SD = 11.37$ years). All attendees possessed a valid driver's license and reported driving a yearly average of 10,856 km ($SD = 10,694$ km, range = 15 – 35,000 km). Participants exceeding or undershooting two standard deviations from the mean driving speed were excluded from further analysis ($n = 5$). Due to elimination of statistical outliers or dropouts of participants experiencing motion sickness ($n = 1$), a final sample size of 48 participants remained.

2.1.2 Apparatus, Task, and Stimuli

We conducted the study in a static driving simulator at the Institute for Automotive Engineering (ika) of RWTH Aachen University, Germany. It consisted of a mock-up car with automatic transmission, a curved screen for front vision (4.8×2 m, $220^\circ \times 50^\circ$ visual range, 5 arcmin/OLP resolution, 1024×600 , 600 Hz refresh rate) and two screens for rear vision (Telefunken A50F446A, 127 cm, 600 Hz refresh rate). We modelled the simulation of the motorway exit via Virtual Test Drive 2.1 (VTD, by VIREs) and operated on Ubuntu Linux 16.04 using VIREs road network editor based on OpenDRIVE road networks for interactively creating and editing the various test scenarios. Participants sat in a modified vehicle chassis. The interior of the car consisted of the original equipment of the car, a tablet used for the secondary task (Dell Latitude 3340 with Windows10, with a 13.30 inch screen), and a numeric keypad (Logilink® ID0120) mounted on the centre console, see Figure 2.

Figure 2

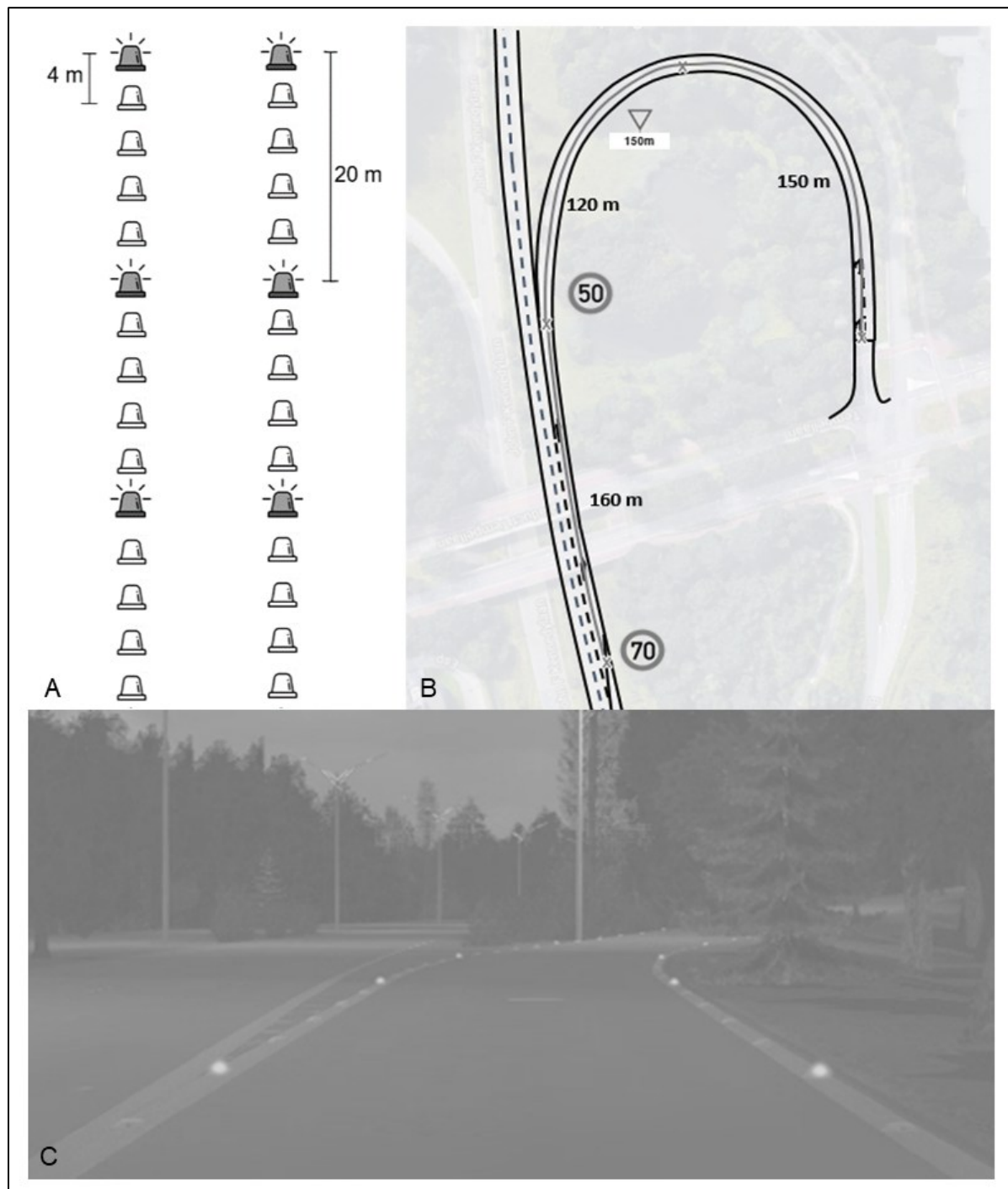
Sketch of experimental setup with the participant position (1), the numeric keypad (2) and tablet for the secondary task (3), and screens of the simulator setup (4 & 5).



A row of simulated red light sources with a distance of 4 m between each two light sources was located on either side of the road. Every fifth light turned on when the driver entered the motorway exit (see Figure 3, part A). In the condition with lights moving towards the driver, the activated lights had the same distance as in the static light condition, but moved one spot further towards the driving direction, creating the illusion of movement at 50 km/h towards the driver. A 50 km/h-sign was placed at the beginning of the clothoid (see Figure 3, part B) to match the real-life motorway exit. Figure 3 (part C) shows the view towards the curve. Driving velocity was measured throughout the exit. There were no further vehicles on the motorway or in the exit. Perception of absolute speed in the static driving simulator is likely to differ from speed perception on the road. However, relations are transferable.

Figure 3

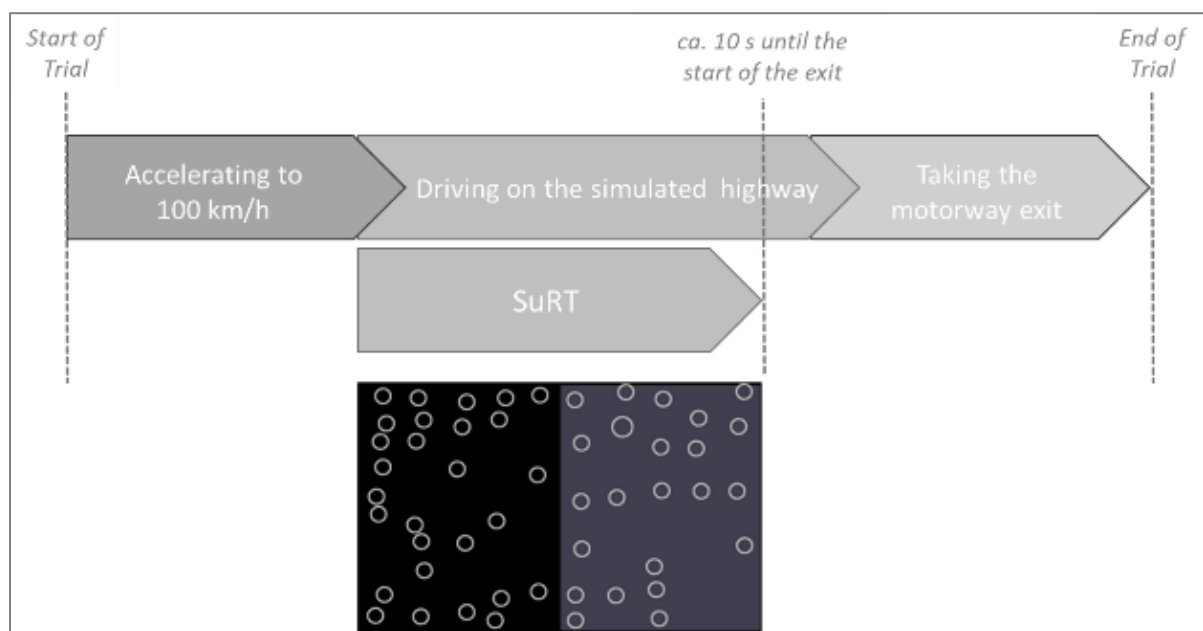
Arrangement of the visuo-spatial light stimuli (A), sketch of the motorway exit (B; drivers coming in from the bottom), and exemplary view of the simulated motorway exit from a position slightly before the 50 km/h-sign with activated (red) lights (C).



In addition to driving on a highway at a recommended speed of 100 km/h and taking a motorway exit when told by the experimenter, participants performed a secondary task. From our observations of driving simulator studies, we have learned that participants tend to form their own hypothesis about the purpose of the experiment. We wanted participants in our study to be naïve to its purpose, which is why we gave them this non-driving related task to draw the attention on an irrelevant aspect to ensure the participant's reaction to the visuo-spatial stimuli was unbiased of their potential subjective conclusions of the reason for the experiment. Further, drivers in the real worlds have to integrate input from a variety of sources at once, while a driving simulator offers a more controlled environment (e.g. Fisher et al., 2011). To prevent that participants focused too much on the driving task, potentially resulting in non-realistic driving behaviour, we asked them to pursue this non-driving related task. In our study, we used the Surrogate Reference Task (SuRT; Mattes & Hallén, 2009) modelled via VisualTask (run on Dell Latitude 3340 with Windows10, with a 13.30 inch screen) mounted on the centre console of the vehicle in the driving simulator. The SuRT displays a black screen with 50 identical white circles (120 pixel circumference, 4 pixel line width), which are randomly scattered across a black screen (Reflexion LED1014DV, 60 Hz refresh rate, 25.5 cm, 1024×600). The aim of the SuRT task is to detect and select one bigger circle, which stands out from the other circles. To select the target, participants pressed a right or a left key on the numeric keypad to move the selection area to the desired position with the target stimulus and confirmed their selection with a key press on a key displaying an arrow pointing upwards. We instructed participants to stop the secondary task before they came close to the motorway exit (approximately 10 s before the beginning of the exit). We therefore assumed that it did not influence participant's reaction to the stimuli. Figure 4 illustrates the start-screen and the select-screen of each trial of the SuRT and the sequence of tasks within one experimental trial.

Figure 4

Illustration of sequence of tasks within one trial. Left: drivers started with accelerating to 100 km/h. Middle: drivers followed the simulated highway and conducted the SuRT in parallel (middle). The picture of the SuRT at the bottom illustrates how a light bar was displayed on one side of the display that could be moved left or right with one arrow key so that the bigger white circle was within this part. After participants confirmed that the bigger white circle was located within this highlighted part, a new pattern of circles was displayed. Right: About 10 s before the start of the motorway exit, drivers stopped the SuRT and took the motorway exit.



2.1.3 Procedure

We conducted the study in April 2018. Participants were welcomed and completed organizational documents and a sociodemographic questionnaire. After taking a seat in the driving simulator, adjusting the seat and buckling up, they received a standardized verbal instruction of their driving task. They had to follow a simulated highway driving at a speed of 100 km/h. When the instructor told them to take the next exit, they were asked to keep driving at 100 km/h until the start of the exit lane and then adjust their speed as they saw fit for the driving situation. We instructed them to drive according to their usual driving behaviour.

The experiment started with a 3-minute introductory drive without taking an exit to get used to the simulator. After this, the SuRT was practiced in a dry run while standing. Then, the instructor told participants that the experiment was about to start. For each trial,

they were placed at the beginning of the simulated road stretch and were asked to accelerate to the instructed 100 km/h. As soon as participants reached 100 km/h, the instructor told them to start the SuRT. About 10 s before the highway exit, participants were told to stop performing the SuRT and to take the next highway exit. Each participant completed three experimental drives, encountering all three light conditions (within-subjects-factor; static lights, moving lights, and baseline) once in fully balanced order. Each drive of these three drives in total ended at a stop sign after the participants took the exit. One drive lasted about 105 s, depending on how fast drivers accelerated at the beginning and how fast they took the curve. Before each condition, the car in the simulation was placed back at the beginning of the simulated highway. After all experimental drives, we debriefed the participants about the purpose of the study.

2.1.4 Design

We based the study on a 2 x 3 within-subject design with repeated measures on the within-subjects factor *time* after stimulus onset (2 levels; t_0 being stimulus onset and t_4 being 4 s after stimulus onset) and the within-subjects factor *light condition* (3 levels; static lights, lights moving towards the driver, and a baseline without lights). We balanced the sequence of the conditions over all participants. The dependent variable was driving velocity in km/h. Significance was tested at $\alpha = .05$.

2.2 Results

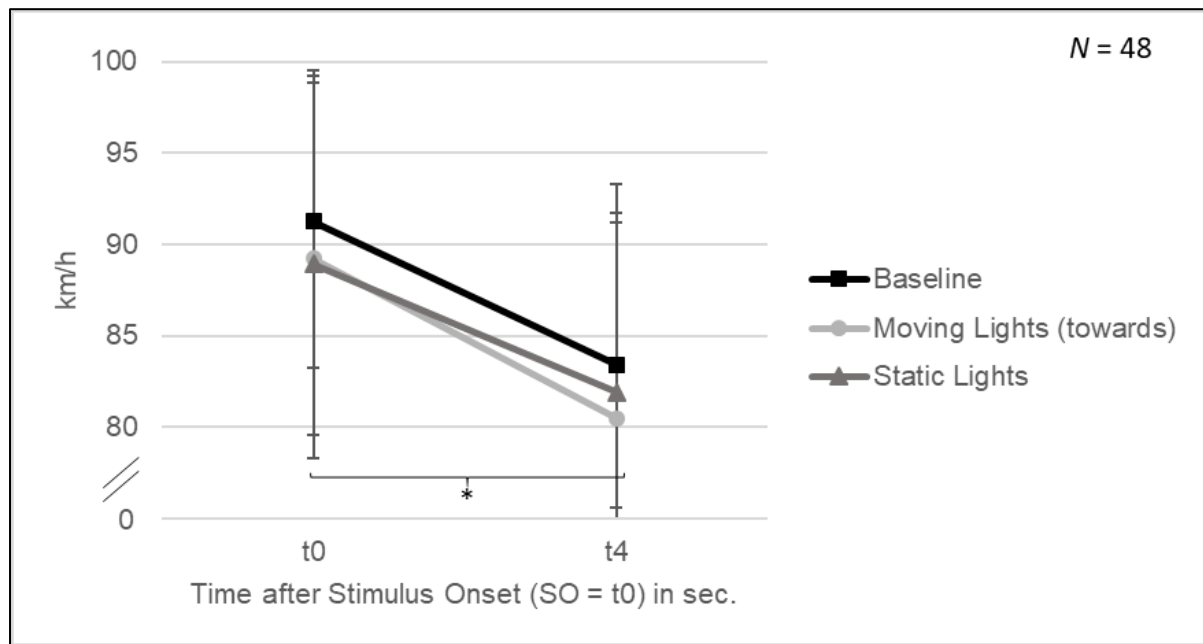
MATLAB Version 2018a was used for the analysis of the quantitative data received from the simulator tests. The simulator logged various parameters during each test drive like the global position of the driver's own vehicle (*ego vehicle*), ego vehicle velocities and accelerations in x-, y- and z- directions, and the lateral distance from the lane reference line. The log files also contained time stamps and distances from stimulus onset at each logged data point (10/s). Please note that stimulus onset can have slight variations, as the light stimuli were triggered by a trigger point placed on the road less than 10 cm before the position of the first light. Due to specifications of the driving simulator, RTs were not monitored in ms. Rather, the simulator sends regular updates on the parameters such as speed or pedal position about ten times per second. For this reason, we interpolated data to the investigated timestamps from the two adjacent time stamps, which were about one tenth of a second apart from one another, varying around the investigated time stamps.

We continued the analysis using IBM SPSS Statistics 23. We conducted a 2 x 3 ANOVA with repeated measures on the within-subjects factor time (2 levels; t0 and t4) and the within subjects-factor light condition (3 levels; baseline, lights moving towards the driver, and static lights). Mauchly's test on sphericity was not significant, neither for the main effect for light condition, $p = .672$, nor for the interaction between time and light condition, $p = .723$. It is therefore reasonable to conclude that the variances of differences are not significantly different. The ANOVA revealed a significant main effect for time, $F(1, 47) = 90.18$, $p < .001$, $\eta_p^2 = .66$, and a non-significant trend towards a main effect for light condition, $F(2, 94) = 1.82$, $p = .084$, $\eta_p^2 = .04$. The interaction was not significant, $F(1, 94) = 0.71$, $p = .247$, $\eta_p^2 = .02$.

To investigate our hypotheses, we conducted three paired post-hoc t-tests (one-tailed) for differences between light conditions at t4, using Bonferroni adjusted alpha levels of .017 per test (.05/3). Results indicated that drivers in the static lights condition ($M = 81.89$, $SD = 11.37$) did not drive significantly slower at t4 than in the baseline ($M = 83.40$, $SD = 7.79$), $t(47) = 1.00$, $p = .161$, $d_z = .14$. Further, results indicated that drivers in the condition with lights moving towards the driver ($M = 80.49$, $SD = 11.24$) did not drive significantly slower at t4 than in the baseline, $t(47) = 1.76$, $p = .043$, $d_z = .25$. Thirdly, results indicated that drivers in the condition with lights moving towards the driver did not drive significantly slower than in the condition with static lights, $t(47) = -0.87$, $p = .194$, $d_z = .13$. The data does not support our hypotheses. Results are displayed in Figure 5.

Figure 5

*Velocity results in the simulator study in km/h at stimulus onset (t_0) and 4 s after stimulus onset (t_4) for the three light conditions baseline, static lights, and lights moving towards the driver. Error bars depict standard deviations. Note: *: $p \leq .001$.*



2.3 Discussion

We conducted a simulator study in a static driving simulator to determine the influence of visuo-spatial stimuli on driving behaviour and speed perception in a simulated motorway exit. For this, we tested static lights and lights moving towards the drivers and compared driving behaviour, operationalized as driving velocity, to a baseline.

We found that driving speed was always lower 4 s after stimulus onset, potentially moderated by the curve in the motorway exit. In general, this describes adaptive behaviour of drivers entering a motorway exit (see Nash et al., 2016). The non-significant trend for light condition could suggest that the three light conditions might have a general impact on driving velocity. When investigating our hypotheses, we did not find a significant difference between lights moving towards the driver and the baseline without lights at t_4 . However, when looking at alpha without the Bonferroni-correction, results indicate at least a trend towards significance. This could be a first indication that lights moving towards the driver could have a certain influence on driver's speed selection. This would be in line with earlier studies distorting visual information in the driving context (e.g. Thaler & Sunstein, 2008; Gates et al., 2008).

It is possible that the lights in the simulator did not induce an optic flow effect as described by Feria et al. (2003), Gibson (1950), and Palmisano (2002). More specifically, it is possible that the sitting position in the simulator did not allow participants to see the stimuli in the periphery, which makes illusions on optic flow more compelling (see Palmisano, 2002). Another possible explanation could be that the driving situation of driving a curve in the simulator after constantly driving straight could have been too complex for our participants. They might have selected information that was relevant for the task of driving the curve in the simulator and it might not have been possible for them to allocate any resources from the already quite complex driving task to the light stimuli (see e.g. Wickens, 1981). Furthermore, driving in the simulator could have led to an experimental bias: drivers might not have felt to be driving too fast for the simulated driving situation. More specifically, participants might have felt safe with the information they were using for the driving task. Therefore, the experimental stimuli in our study could have been irrelevant for their speed selection, or the visuo-spatial stimuli influenced their speed choice only slightly, but not as much as we initially expected in comparison to the lights moving towards the driver.

In addition, other factors such as auditory (Macadam, 2003), haptic (Sigrist et al., 2013), or proprioceptive factors (Reymond et al, 2001) could have an influence on speed perception as well. In the static driving simulator with only the visual feedback present, drivers might have been unaware of the degree of speed adjustments. We reasoned that an application in a natural traffic setting would allow us to control for this effect and we could investigate the applicability of the simulator results in the field. More precisely, according to Kemeny and Panerai (2003), Salmon et al. (2014), and Salmon et al. (2012), e.g. processing of visual stimuli is likely complemented by the driver's inferential hypothesis about the behaviour of other road users. Therefore, drivers might have needed this feedback to react as we had hypothesized.

To investigate our findings further, we conducted Study 2 described in this paper. As we did not encounter any dangerous driving behaviour in the simulator (Study 1), we deemed it justifiable to implement the system in a naturalistic traffic situation. To foreshadow the results of Study 2: We did find a significant difference between lights moving towards the driver and a baseline and between static lights and a baseline.

3. Study 2: Field Test

Following the simulator study and to investigate our hypotheses in a naturalistic driving setting with a larger sample, we conducted a field test at the site that the simulation for

the driving simulator study had been modelled after. Within the MeBeSafe project, the same system as tested in the first study was implemented in a motorway exit for a field test to investigate the potential of the tested system for traffic safety. This gave us the possibility to control for a potential simulator effect, in which drivers might not have seen the need to react.

3.1 Method

3.1.1 Sample

We collected the data in a fully anonymous field trial and did not record any personal information. We informed citizens of Eindhoven, Netherlands, where we conducted Study 2, via local communication channels that a field trial on the test site at Kennedylaan would be conducted within the scope of the MeBeSafe project. It is likely that a majority of residents around the exit took it frequently. A survey in residential areas surrounding the exit found that 26 % of respondents used the exit every day or working day (15 %), or at least once a week (14 %; Ljung Aust et al., 2020).

The dataset analysed in the present paper is part of a larger dataset of the MeBeSafe project. The overall field test included eleven tested scenarios with 198,309 drivers taking the exit over a period of eleven weeks (for details, see Ljung Aust et al., 2020). In the present paper, we focus on 3 scenarios to draw a direct comparison with the simulator study described in the first study to investigate our hypotheses, namely static lights, lights moving towards the driver, and a baseline without lights, leading to 47,547 participants. To investigate our hypotheses, the following steps were executed: We included only vehicles who encountered the activated system and excluded drivers who did not activate the system due to following the speed regulations in this traffic situation (see section 3.1.2 for specification), leading to 29,844 participants. In this analysis, we included only those drivers, whose driving speed was two standard deviations ($SD = 8.68$ km/h) above the mean speed of the baseline at stimulus onset ($M = 71.71$ km/h), resulting in all drivers in the sample for the analysis exceeding 89.07 km/h at light onset. This leads to a sample size of 1,041 drivers for the three conditions considered for this publication (baseline: $n = 333$, lights moving towards the driver: $n = 337$, static lights: $n = 371$).

3.1.2 Apparatus, Task, and Stimuli

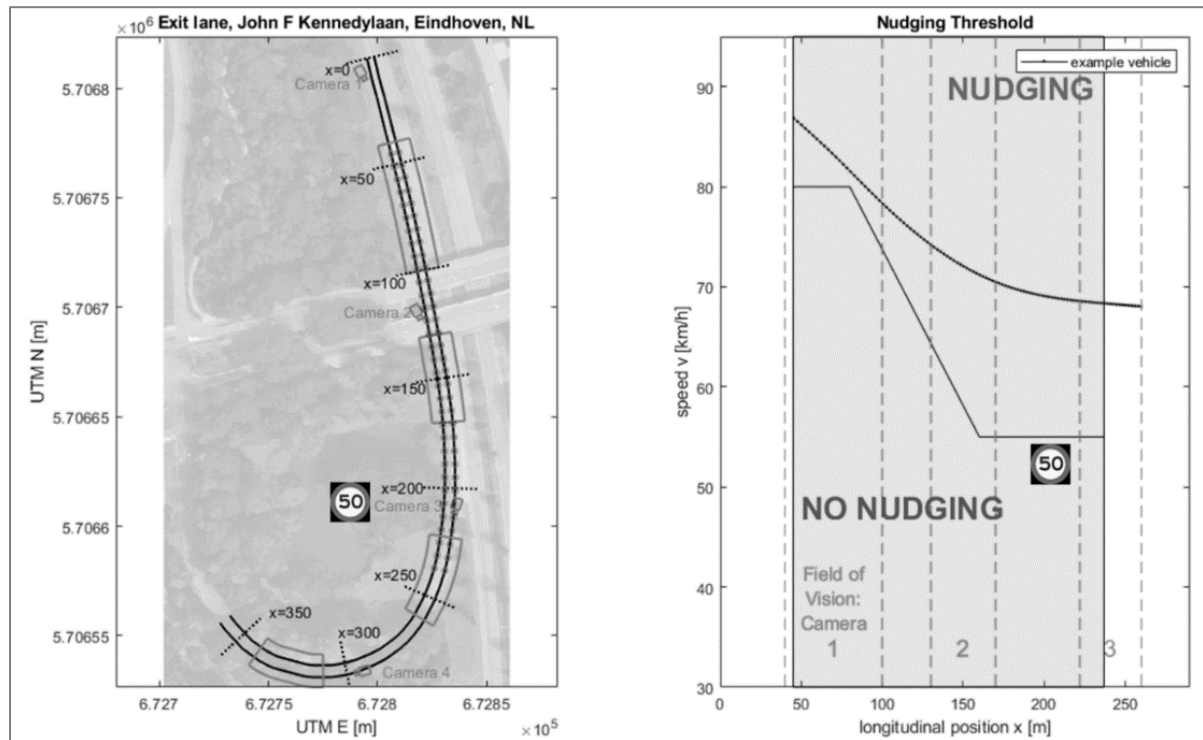
We conducted the field test at the motorway exit J.F. Kennedylaan to Tempellaan in Eindhoven, Netherlands. For the field test, roadside marking lights were installed. We used 40 LED road studs (Sernis, *SR-045 DMX RGBW*) on each side of the exit lane for a total

length of 240 m, leading to 6 m between two pairs of lights, measured on the inner part of the curve (see Figure 6 on the left). This was slightly different to the simulator study, where two lights were 4 m apart. In a qualitative pre-test with 6 participants in a static driving simulator, participants did not notice this difference when asked if they noticed any difference between different spacings, neither spontaneously nor when being made aware of it.

The main difference to the simulator study was that vehicles' speed was measured and lights were only displayed if speed exceeded a certain threshold (see section on apparatus, task, and stimuli). Displaying such a measure to every driver could lead to habituation (see e.g. Gates et al., 2008; Hautzinger et al., 2011), especially when it is likely that many drivers might drive through the system on a daily basis. We therefore measured the vehicles' speed using three thermal cameras (Axis, *Q1942-E Thermal*) along with computer vision algorithms. Camera 1 was placed at $x = 0$ m of the coordinate system, camera 2 at $x = 112.37$ m, so 112.37 m after the first camera, and camera 3 was placed at $x = 201.37$ m (see Figure 6 on the left). It was possible to reliably detect if a car had taken the exit lane from $x = 50$ onwards, which is also the stimulus onset. Each vehicle was assigned a distinct ID that related to all cameras. Thermal cameras are unaffected by day/night changes, ensure data privacy, and detection is not distorted by e.g. headlights. The vehicles fulfilling the nudging criteria (exceeding the speed threshold and a minimum distance of one stimulus length (96 m) between two vehicles) were identified by an intelligent decision control logic (see Ljung Aust et al., 2020). For more details on the computer vision algorithms, see Berghaus et al. (2020).

Figure 6

On the left: Set-up of the field test with thermal cameras and roadside marking lights. The beginning of the lights is the beginning of the exit lane. On the right: Nudging threshold based on speed over the course of the exit lane (retrieved from Ljung Aust et al., 2020, p. 95).



When drivers entered the exit lane with a speed above a predefined threshold (10 % above the speed limit, see Figure 6 on the right), they saw, according to the light conditions, static lights or lights moving towards them. Every fourth light turned on when the driver entered the motorway exit. In the condition with lights moving towards the driver, the activated lights had the same distance as in the static light condition but moved one spot further towards the driving direction at 50 km/h, creating the illusion of movement. Lights were coloured in red (#FF0000/255,0,0), brightness was set to 50 % of possible brightness of the LEDs. A 50 km/h-sign was located at the beginning of the clothoid ($x = 205$ m, 165 m after stimulus onset).

3.1.3 Procedure

The field test was conducted from October 2019 to December 2019. The baseline was measured from October 21st to October 28th, 2019, the static lights condition was tested from December 2nd to December 9th, 2019, and the moving lights condition was measured from November 25th to December 2nd, 2019. All drivers entering the exit lane of the field test

location above the pre-defined threshold saw light patterns according to the activated scenario of that week when above the pre-defines threshold (see section on apparatus, task, and stimuli). There were no instructions, as natural driving behaviour was observed.

3.1.4 Design

We based Study 2 on a 2 x 3 mixed design with repeated measures on the within-subjects factor *time* after stimulus onset (2 levels; t_0 being stimulus onset and t_4 , being 4 s after stimulus onset) and the between-subjects factor¹ *light condition* (3 levels; static lights, lights moving towards the driver, and a baseline without lights). The dependent variable was driving velocity in km/h. Significance was tested at $\alpha = .05$.

3.2 Results

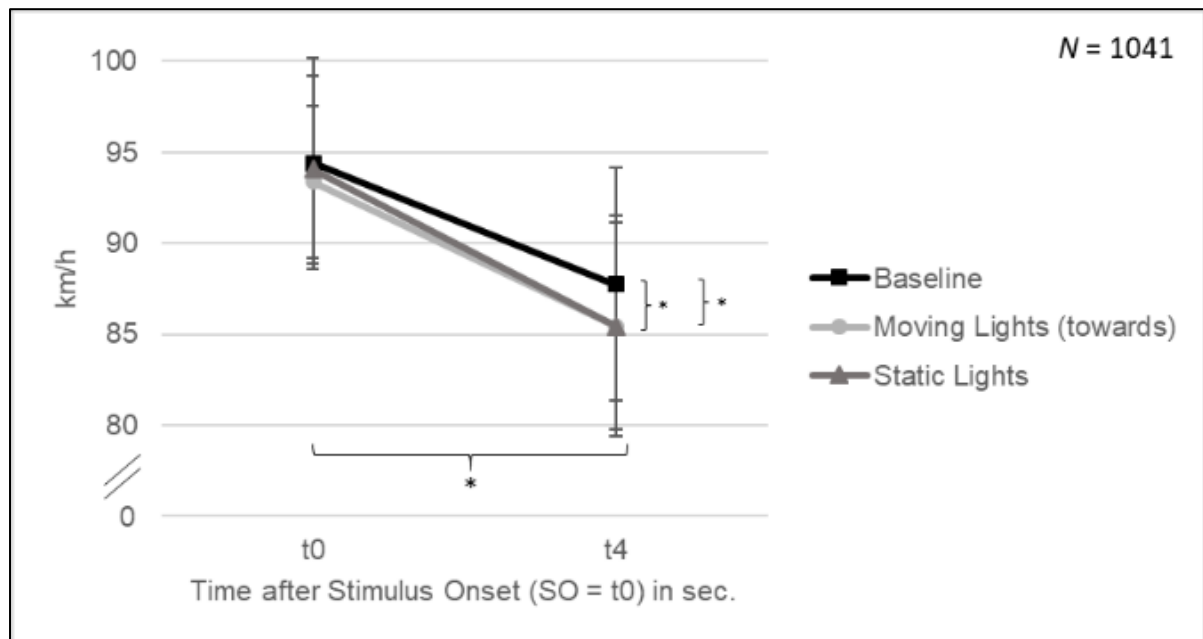
We conducted the data analysis with IBM SPSS Statistics 23. We conducted a mixed 2 x 3 ANOVA with repeated measures on the within-subjects factor *time* (2 levels; t_0 and t_4) and the between subjects-factor *light condition* (3 levels; baseline, lights moving towards the driver, and static lights). The ANOVA revealed a significant main effect for time, $F(1, 1038) = 3766.51, p < .001, \eta_p^2 = .78$, a main effect for the between-subjects factor light condition, $F(1, 1038) = 9.46, p < .001, \eta_p^2 = .02$, and a significant interaction between time and light condition, $F(1, 1038) = 20.92, p < .001, \eta_p^2 = .04$.

To investigate our hypotheses, we conducted three post-hoc t-tests (one-tailed) for independent samples to test for differences between light conditions at t_4 , using Bonferroni adjusted alpha levels of .017 per test (.05/3). Results indicated that drivers in the static lights condition ($M = 85.42, SD = 6.06$) drove significantly slower at t_4 than in the baseline ($M = 87.72, SD = 6.39$), $t(702) = 4.91, p < .001, d = .37$. This supports our hypothesis. Further, results indicated that drivers in the condition with lights moving towards the driver ($M = 85.44, SD = 5.68$) drove significantly slower at t_4 than in the baseline, $t(668) = 4.89, p < .001, d = .38$. This supports our hypothesis. Thirdly, results indicated that drivers in the condition with lights moving towards the driver did not drive significantly slower than in the condition with static lights, $t(706) = 0.05, p = .482, d = .003$. The data does not support our hypothesis. Figure 7 illustrates the results.

¹ We are conservatively assuming a between-subjects design, as we cannot determine if any driver might have taken the exit in all testing conditions and might have seen just one, two, or all three light conditions

Figure 7

*Velocity results in the field test in km/h at stimulus onset (t_0) and 4 s after stimulus onset (t_4) for the three light conditions baseline, static lights moving towards the driver, and moving lights. Error bars depict standard deviations. Note: *: $p \leq .001$.*



3.3 Discussion

In Study 2, we conducted a field test to determine the influence of visuo-spatial stimuli on driving behaviour and speed adaption in a natural traffic environment at a motorway exit. For this, we tested static lights and lights moving towards the driver and compared driving behaviour to a baseline without lights. Driving behaviour was operationalized as driving velocity.

The main effect for time in all comparisons showed that driving speed was lower 4 s after stimulus onset, potentially moderated by the curve in the motorway exit. Again, this describes adaptive behaviour of entering a motorway exit (see Nash et al., 2016).

We specifically expected drivers to react with adapting a lower velocity when we presented static lights compared to a baseline without light stimuli. Further, we expected drivers to react with adopting a lower velocity when lights moving towards the driver were presented compared to a baseline without light stimuli. Our results supported both hypotheses. More specifically, the findings of Study 2 suggest that lights moving towards the driver are likely to have altered the driving behaviour of our participants by influencing the optic flow, which is in line with Feria et al. (2003), Gibson (1950), and Palmisano (2002). However, as we saw

the same pattern of results for static lights, it is likely that displaying lights in general could have led to driver's reducing their speed more in comparison to the baseline without lights. This could be because of the warning character of the lights (see Kahneman, 1973; Lidwell et al., 2010).

This is in line with the results not revealing any significant difference between the two light conditions. This finding could suggest that the lights moving towards the driver did not influence the optic flow (Gibson, 1950) as we had assumed. According to Zhang et al. (2013), the visual periphery is also biased towards centrifugal directions, giving the impression that static objects are indeed moving. This could explain why we did not find a difference between static lights and lights moving towards the driver: Drivers could still have perceived a certain movement component, leading to similar results of static lights and lights moving towards the driver.

Because statistical power of the study was very high, we can assume that any residual effect must have been very small and would thus most likely be negligible.

4. General Discussion

We conducted two studies to determine the influence of visuo-spatial stimuli on driving behaviour, in the form of lights implemented in the road infrastructure. Study 1 was conducted in a static driving simulator, whereas Study 2 was conducted in a naturalistic driving setting in the field. Based on various considerations regarding the perceived urgency drivers might see to react (e.g. Summala, 2000), we applied a timeframe of 4 s as the time where drivers could have reacted in adapting their velocity (Gates et al., 2007; Green, 2000).

In both studies, we found that drivers showed a lower velocity 4 s after stimulus onset, showing that drivers always drove more slowly 4 s after stimulus onset. This is likely moderated by the curve of the motorway exit, which leads to drivers slowing down (see e.g. Nash et al., 2016).

Further, the results of Study 1 did not reveal a speed difference between static lights and the baseline without lights at t4. The results of Study 2, tested in the field, however, showed that participants in the condition with static lights drove slower compared to a baseline. We found the same pattern of results for lights moving towards the driver. Results of Study 1 did not reveal a statistically significant difference between lights moving towards the driver and the baseline but gave a first indication that lights moving towards the driver could have a certain influence on driver's speed selection, which is in line with the optic flow

paradigm (e.g. Gibson, 1950). The results of Study 2 supported this and showed that participants in the condition with lights moving towards them drove slower compared to a baseline.

Therefore, in Study 2, any kind of tested light condition did have an effect on driven velocity when compared to a baseline. This suggests that both light conditions, namely static lights acting as a warning (see Donald, 1988; Edworthy & Adams, 1996) and lights moving towards the driver according to the optic flow paradigm (see Feria et al., 2003; Gibson, 1950; Palmisano, 2002), were likely more prominent and relevant for drivers in the field test than in the simulator study. A potential reason could be the method of the driving simulator for testing solutions targeting sensory information: Previous studies were often conducted in naturalistic traffic (see Thaler & Sunstein, 2008; Gates et al., 2008), or in the case of e.g. Godley et al. (2004) in a high-fidelity driving simulator. This information could have been missing in our static simulator study.

Another reason for the difference between the two studies could be that the artificial simulator situation might have been too novel to our participants. In the field test, on the other hand, drivers are likely to have been more familiar with the natural driving situation of leaving a motorway, so the lights could actually help them in adjusting their driving speed, as drivers naturally pay attention to relevant information close to the road.

Another potential reason for differences between Study 1 and Study 2 could be the salience of the light stimuli. The light stimuli in the simulator study were projected to the screen of the simulator by standard projectors. They were not light emitting by themselves, but rather gave the impression to. In the field test on the other hand, actual lights were integrated into the road, thus leading to a higher stimulus salience, which could have made it easier to draw driver's attention and facilitate a reaction from drivers (see Bordalo et al., 2021). However, we did not find a difference between static lights and lights moving towards the driver in any of the two studies. As outlined, this could be due to similar perception of movement in the periphery (Zhang, 2013).

It should be mentioned that traffic flow in general has been reported to play a role on how speed is adjusted: Khan et al. (2021) outlined the role of distance headway in driver reactions and described that responses are quick with small distance headway and vice versa. Furthermore, Iftikhar et al. (2020) pointed out personal factors such as driving style affecting how drivers might react. The presented studies however focused on the effect of the described visuo-spatial stimuli on driver's speed adaptation while only including responses of drivers who had a distance headway of more than 96m. However, the effect of such measures in

more congested traffic situations as e.g. described by Iftikhar et al. (2020) should be subject to future research.

The question arises of which nature the relationship between visuo-spatial stimuli and perceived driving speed is. A differently perceived driving speed provoked by additional visuo-spatial stimuli in comparison to the perceived driving speed under baseline conditions does not necessarily have to lead to an adjusted driving speed, even though it is likely that lights moving towards the driver influence the optic flow (Feria et al., 2003; Gibson, 1950; Palmisano, 2002). It is however possible that the drivers in the simulator did perceive their driving speed differently when encountering any light condition compared to the baseline, but did just not see the need to react (see e.g. Papakostopoulos et al., 2017). Follow-up studies should aim at examining the linearity of actually driven and perceived speed further.

Future research could determine the role of driving experience in the successful integration of visuo-spatial cues. However, it is possible that visuo-spatial stimuli alone target speed choice and, even before that, speed perception, insufficiently. In the present study, we assumed that the most appropriate modality for speed perception was the visual modality. However, stimuli of different sensory modalities could interfere (see Morey et al., 2011). In the context of driving, many stimuli from different sources, for example the vestibular, visual, and auditory system, need to be integrated at once (see Papakostopoulos et al., 2017). Therefore, the role of other sensory information in speed perception should be subject to future research. More specifically, a study by Lukas et al. (2010) found a visual-dominance effect in experiments with simultaneously presented bimodal (visual and auditory) stimuli. When participants had to tend to auditory stimuli, visual stimuli interfered more than vice versa. In line with the modality-appropriateness-hypothesis (Welch & Warren, 1980), attention is drawn to the appropriate modality. In this vein, it is possible that the visual-dominance effect is not as pronounced in speed selection as we assumed. Further research should evaluate the role of auditory factors and their interaction with visual stimuli in speed perception.

5. Conclusion

This paper investigated the influence of dynamic visuo-spatial stimuli presented as lights to prevent habituation effects on speed adaptation in a simulator study and a subsequent field test in real traffic. While not finding any differences in driving speed in the simulator study, which could be due to the simulator specifications, displaying lights to speeding drivers led to lower driving speeds both with static lights and with lights moving towards the driver in the field test. This could be due to the general warning character of red lights in

traffic. However, the dynamic component of the lights did not differ from static lights, suggesting that the moving component did not influence the optic flow. The underlying perceptual reasons for this should be investigated further. More specifically, future studies should research the effect of the solution not only on speed choice but also on speed perception in general. Despite the potential limitations, we found the solution to display lights in the driving context to be generally effective. The results provide further information on how measures targeting sensory perception can influence speed adaptation. As accident rates are still high even though different measures already exist, measures such as the one described in this paper should be researched further to reach Vision 0 for traffic safety.

Declarations

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CRedit authorship contribution statement

Anna-Lena Köhler: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. Iring Koch: Validation, Writing – review & editing. Stefan Ladwig: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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**Investigating the Influence of Visuo-Spatial Stimuli on Driver's Speed Perception: A
Laboratory Study**

Anna-Lena Köhler¹ *, Maren Klatt¹, Iring Koch², and Stefan Ladwig¹

¹ Institute for Automotive Engineering (ika)
RWTH Aachen University
Aachen, Germany

² Institute for Psychology
RWTH Aachen University
Aachen, Germany

*anna-lena.koehler@rwth-aachen.de

Abstract

Driving at an inappropriate speed is a major accident cause in the EU. Understanding the underlying sensory mechanisms can help to reduce speed and increase traffic safety. The present study investigated the effect of visuo-spatial stimuli on speed perception using an adaptive countermeasure to speeding based on a manipulation of optic flow. We added red lights on both sides of a simulated road. We expected speed to be perceived as faster when lights moved towards drivers due to increased optic flow, whereas we expected static light stimuli to not alter the optic flow and thus not influence speed perception. Two experiments applied the method of constant stimuli. To this end, participants encountered several trials of two video sequences on a straight road. A reference sequence showed the same traveling speed while test sequences varied around different traveling speeds. Participants indicated which sequence they perceived as faster, leading to the calculation of the point of subjective equality (PSE). A lower PSE indicates that the speed in this experimental condition is perceived as faster than in another experimental condition. Experiment 1A did not show a difference between PSEs of static and oncoming lights. Because participants had counted reflector posts for speed estimation, we removed these reflector posts in Experiment 1B and found a lower PSE for oncoming lights. Thus, such light stimuli may have an effect only in situations without other competing visual stimuli supporting speed perception. Future research should investigate whether speed perception is indeed a primarily visuo-spatial control task or whether other sensory information such as auditory factors can have an influence as well.

Keywords: *speed perception, safe speed, traffic safety, adaptive traffic intervention, optic flow*

Significance Statement

Inappropriate speed remains a major cause of accidents. There is a variety of interventions aiming at lowering driving speed inappropriate for a given context. Countermeasures to speeding in the driving infrastructure can target every driver in potential areas. Understanding the mechanisms in speed perception can help to develop better interventions. The present two experiments investigated the role of visual stimuli in speed perception based on a dynamic light-based intervention that led to lower driving speeds in a previous simulator study and field test (Köhler et al., 2022). Our findings show that oncoming lights lead to lower perceived traveling speed, but only when there are no other salient visual stimuli that support speed perception. In sum, the findings provide valuable insights for future development of countermeasures targeting speeding.

Introduction

Inappropriate speed is one major accident cause in the European Union, with 53 % of fatalities having occurred on inter-urban roads in 2020 (European Commission, 2022) and traffic accidents still being the number one cause of death for children and young adults (World Health Organization, 2018). It is likely that accidents are multicausal events with a variety of potential causes and the human factor being one of them (Laaraj & Jawab, 2018). For instance, drivers likely often adopt traffic behavior that is inappropriate for the traffic situation, that is, inattention to possible risk or inappropriate speed (Karlsson et al., 2017). Furthermore, even a slight increase in speed could increase accident rates (Quddus, 2013) and, according to Elvik et al. (2004, 2019) and Hauer (2009), the higher the driving speed, the more inflexible could boundaries for action alternatives become. In this vein, this paper focuses on drivers' speed perception as one influencing factor in traffic safety.

Causes for speeding are manifold and could either be conscious, ranging from person-related factors, such as attitude towards speeding, over situational factors, such as being late for an appointment, to social factors, such as peers challenging to drive faster (Wiafe et al., 2020). These aspects could be the reason that drivers might willingly decide to speed and thus enter a so-called dread zone, which means that they voluntarily leave their comfort zone where they feel safe (see Bärghman et al., 2015). According to the field of safe travel hypothesis (FoST; Gibson & Crooks, 1938; Papakostopoulos et al., 2017), drivers usually work towards staying safe and comfortable in traffic by keeping up safety margins between themselves and their surroundings. The FoST consists of the subjective impression where the driver feels safe and the objective field, in which the vehicle can be operated safely (Gibson & Crooks, 1938). As there is no empirical evidence for the FoST according to the best knowledge of the authors, but it is mostly used to describe driver's feeling of safety, Kolekar et al. (2020) operationalized the Driver's Risk Field (DRF) in a study on obstacle avoidance. Results indicated that the DRF is wider than the vehicle itself. This emphasizes that the subjective perception of risk likely differs from objective parameters, which suggests that both areas should be investigated when it comes to traffic safety. According to Papakostopoulos et al. (2017), the FoST narrows along with the edges of the road, indicating that the driving environment and the cues that are available in it could potentially subliminally influence how drivers adjust their speed. This paper aims at investigating the role of cues in the driving environment on driver's speed perception.

Horswill and McKenna (1999) conducted two video-simulation studies and found that visual and auditory information, even if distorted, were the dominating modalities for processing information on speed, especially because drivers would tend to not look at their speedometers even if speed control would be required for the driving task. Driving speed decreased especially when internal car noise was raised. The relationship between objective information on speed and subjective speed perception has also found to be unstable in two speed estimation studies in a simulator and in a field test (Denton, 1980) and in a study on estimation of distances outside the driving context (Wu et al., 2004). This unstable connection between objective and subjective perception is a factor especially when it comes to the distortion of speed perception when slowing down after a long time traveling at higher speeds, which is called the speed adaptation effect (Denton, 1996). Stimuli in several perceptual modalities, such as proprioceptive (Kemeny & Panerai, 2003), vestibular (Macadam, 2003), or haptic information (Sigrist et al., 2013), can influence speed perception, with visuo-spatial stimuli likely having the biggest influence (see Köhler et al., 2022).

To facilitate safer traffic, the concept of self-explaining roads (SER) plays a role in designing a safe traffic environment (see Theeuwes, 2021). This means that road users know how to behave just by design of the driving environment. Selecting relevant information is crucial to successfully accomplish the driving task. Drivers have learned which objects to expect in the driving environment, making information selection efficient. In a nutshell, a well-designed road environment benefits the selection of appropriate and safe behavior. However, well-learned behavior can make drivers prone to bias and relevant cues can be overlooked, especially under high workload (Theeuwes, 2021).

In driving, a variety of information needs to be integrated by the driver's information processing system at the same time to be able to accomplish the driving task, with speed control as one of several parallel tasks (Papakostopoulos et al., 2017; Stapel et al., 2019). Visual information has been described as one of the primary sources of information while driving (Macadam, 2003). According to Posner et al. (1976), visual attention needs to be allocated actively, requiring cognitive resources, and thus limiting processing input from other modalities. The latter is a potential reason for the advantage of visual stimuli in spatial tasks. As Gibson (1950) and Krüger et al. (1999) indicated, drivers are constantly monitoring both their own position and that of their vehicle in the driving environment. Therefore, speed control of a vehicle can be regarded a spatial control task (see also Köhler et al., 2022). This is supported by Ward et al. (2000), who stressed that vision is more prominent in spatial localization tasks than, for example, auditory information (see Lukas et al., 2010, 2014).

Another indicator for the dominance of visuo-spatial information in speed perception is the optic flow, which means that humans perceive their own driving speed relative to the speed of the environment (see, e.g., Gibson, 1950; Manser & Hancock, 2007; Palmisano, 2002). Among others, Ding et al. (2020) and Bergh Alvergren et al. (2019) used transverse line markings that move closer and closer together, thus creating the impression of becoming faster to decelerate drivers or cyclists, respectively. Both studies used visual cues in natural driving contexts, leading to lower driving speeds. Further, continuously decreasing spacing between transverse-bar road markings did lead to a reduction of mean speed by up to 4 mph (ca. 6.5 km/h) in a study by Gates et al. (2008). Therefore, the faster objects pass by, the faster speed is perceived. This has also been shown by Manser and Hancock (2007), who placed stripes on a tunnel wall that gradually decreased in width, and thus induced a feeling of acceleration. Palmisano (2002) found an effect of stereoscopic pattern on one's own speed. Three-dimensional information about self-motion provided more information about driven speed than two-dimensional information and had the ability to radially expand optic flow, making illusions on optic flow more compelling. These countermeasures to speeding suggested that visuo-spatial stimuli have the potential to influence driver's speed selection. To prevent situations in which drivers might not be aware of inappropriate speed, Köhler et al. (2022) conceptualized and studied a countermeasure to speeding by aiming at giving drivers an impression to be driving faster than they did, similar to the described studies with transverse line markings (Bergh Alvergren et al., 2019; Ding et al., 2020).

In a driving simulator study followed by a field test, Köhler et al. (2022) tested lights that were installed on both sides of the road, being activated if a driver approached at too high driving speeds. They investigated the influence of visual stimuli on speed adaptation in the form of red light-emitting spots. To prevent habituation effects (see, e.g., Hautzinger et al., 2011), the intervention was activated only for speeding drivers (see Köhler et al., 2022). Lights also have a higher stimulus salience than other static stimuli applied in the driving environment (see, e.g., Gates et al., 2008; Manser & Hancock, 2007; Palmisano, 2002). Choosing red lights was due to the color red being associated with stopping (Lidwell et al., 2010) and drivers reacting to red lights with caution in general (e.g., Edworthy & Adams, 1996; Norman, 1988). The sides of the road were chosen as a suitable location for a measure targeting driver's speed perception when drivers might not be aware of driving too fast, because the sides of the road are usually in the driver's periphery, which are exposed to faster motions (Zhang et al., 2013). The lights were then activated either moving towards the driver, thus highlighting the optic flow (e.g., Gibson, 1950), or were statically illuminated (non-moving).

Participant's speed adaptation when encountering either oncoming lights or static lights was compared to a baseline in a simulator study and in a subsequent field test by Köhler et al. (2022). A significantly lower speed for both static lights and oncoming lights, each compared to a baseline, was found in the field test, indicating that visuo-spatial cues in general can have an impact on driving speed, independently from the movement condition. The study's results did, however, not reveal a significant difference in driving speeds between static lights and oncoming lights. It therefore remained open whether the presence of lights in general or one of the two movement conditions, static or oncoming lights, influenced driving speed more.

The present paper targets the influence of sensory factors on speed perception, specifically visual information, by investigating the sensory principles of the measure described by Köhler et al. (2022) more closely. The results of the field test by Köhler et al. (2022) suggested that participants drove more slowly when they encountered light stimuli, while the situation in the driving simulator was possibly not perceived to be critical enough to trigger a reaction by adjusting the driving speed as observed in the field test. Therefore, the present paper does not focus on actual speed selection as an indicator of speed perception but targets the influence of visuo-spatial stimuli on speed perception itself.

For this, we applied the method of constant stimuli (Hegelmaier, 1852, cited by Laming & Laming, 1992). In this method, various test stimuli or sequences are compared to a reference stimulus or sequence, which remains constant over the course of the study. The participant then has to decide and indicate via key press which stimulus they perceived as faster. Based on the dichotomous responses of the key press, a binary logistic regression is calculated for the independent variable and every participant. The results of this procedure can then be used to calculate the point of subjective equality (PSE). The PSE has been defined as the .5 probability point at which two stimuli look the same to an observer so that they would choose randomly between them (Kim et al., 2014). It is therefore a measure for the perceived driving speed, or traveling speed when participants are not driving themselves. Pretto et al. (2012), for example, used this method to examine the effects of fog on perceived traveling speed. We investigated the same light conditions as used by Köhler et al. (2022), namely red statically illuminated lights and red oncoming lights. We investigated the effect of the light stimuli on speed perception on a straight road instead of a motorway exit (as did Köhler et al., 2022), as this might influence speed selection since drivers usually slow down when approaching curves (Nash et al., 2016). We examined whether the addition of a movement component in the lights lead to a change in drivers' speed perception. We expected the perceived speed in the condition with oncoming lights to be significantly higher than in the condition with static lights. This means that an

objectively slower traveling speed in the condition with oncoming lights would be perceived to be as fast as an objectively higher traveling speed in the condition with static lights, in line with the optic flow (see Gibson, 1950; Manser & Hancock, 2007; Palmisano, 2002). Unlike Lidestam et al. (2019), who investigated virtual road markings, we tested light spots that were directly implemented on the road surface.

Method

To test our hypotheses, we conducted two experiments, which we refer to as Experiment 1A and Experiment 1B. For practical reasons, we ran Experiment 1A before running Experiment 1B, but both experiments were completely comparable and we therefore report them as one between-subjects experiment.

Sample

We used G*Power (Faul et al., 2007) to estimate our sample size a priori and assumed a medium effect of $d_z = 0.5$ (Cohen, 1988) based on the results of Pretto et al. (2012), who reported medium to large effects regarding the effect of visibility on visual speed. For our mixed design with the within-subjects factor *presentation of lights condition*, henceforth *presentation condition* (2; static lights vs. oncoming lights) and the between-subjects factor *presence of road markings* (2 levels; with road markings and reflector posts vs. without road markings and reflector posts), we calculated that a sample size of 28 participants for each experiment would allow us to detect an effect of this size at $\alpha = .05$ with a power of .82 (see Faul et al., 2007). For a fully counterbalanced design, 28 participants took part in Experiment 1A of the study ($n = 17$ male, $n = 11$ female). The mean age was 25.11 years ($SD = 4.52$ years) with ages ranging from 18 to 44 years. 89.3 % ($n = 24$) were right-handed. All participants had a normal or corrected-to-normal vision and held a driver's license for a mean duration of 7.64 years ($SD = 4.65$ years), ranging from two to 26 years. The number of kilometers that was driven by the participants within a year ranged from 0 km to 30,000 km ($M = 7,694.64$ km, $SD = 7,874.01$ km). All participants were naïve to the purpose of the study and received a monetary compensation of 20 €.

For Experiment 1B, we recruited a larger sample, since it was part of a larger study, but with further considerations regarding power irrelevant for this paper. Thirty-six participants took part in Experiment 1B ($n = 17$ male, $n = 19$ female). This would have allowed us to detect a medium effect of $d_z = 0.4$ (Cohen, 1988). The mean age was 27.42 years ($SD = 10.52$ years) with ages ranging from 18 to 61 years. 88.9 % ($n = 32$) were right-

handed. All participants had a normal or corrected-to-normal vision, 34 participants held a driver's license for a mean 9.88 years ($SD = 10.78$ years), ranging from one to 44 years. The number of kilometers that was driven by the participants within a year ranged from 0 km to 44,000 km ($M = 6,377.06$ km, $SD = 8,454.03$ km). All participants were naïve to the purpose of the study. Participants in Experiment 1B participated voluntarily but did not receive any monetary compensation.

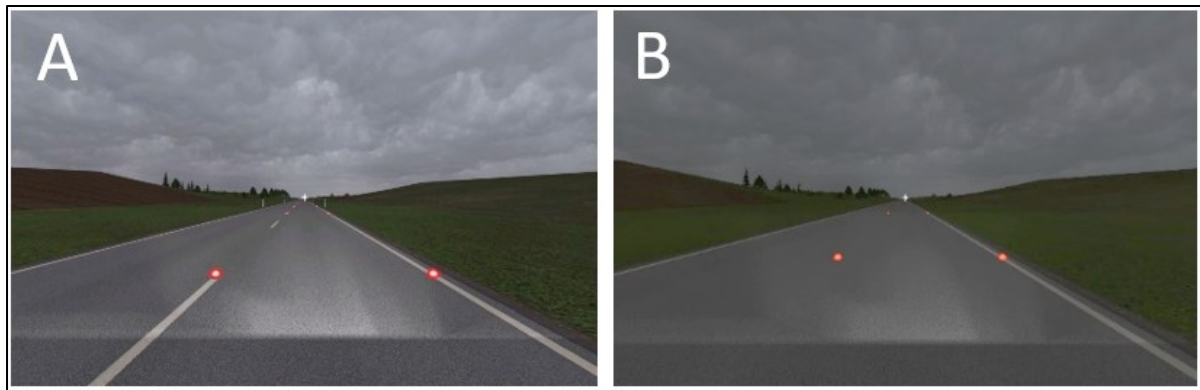
Apparatus, Task, and Stimuli

We programmed the experiment on PsychoPy (2.0) and ran it on Windows10. Participants saw two video sequences per trial. Each trial consisted of a reference sequence and a test sequence. While the reference sequence remained the same over all trials (no light stimuli, traveling speed of 100 km/h), the test sequence varied in tested presentation condition (static or oncoming lights) and traveling speed in the video. We counterbalanced the order of test sequence and reference sequence among participants. For test sequences with static or oncoming lights, we placed lights every 6 m on the road surface to match the specifications of the simulator study by Köhler et al. (2022). As the lights, appearing as standard light studs used on normal roads, were placed directly on the road surface, they appeared smaller when being further away and grew in retinal size as they moved closer.

In Experiment 1A, the lane in the driving direction was separated from the opposing traffic lane by road markings (white broken line, as common on rural roads in Germany). Reflector posts stood on both sides of the road, see Figure 1 part A. The distance between the posts was 50 m and therefore comparable to the distance of reflector posts on German roads. The starting point on the road was the same for all sequences. As we found that 21 out of 28 participants in Experiment 1A might have counted reflector posts to estimate speed, we decided to replicate the experiment (i.e., Experiment 1B), but remove reflector posts and road markings from the videos so that participants could focus solely on the light stimuli, see Figure 1 part B. This allowed us to focus on the influence of the implemented visuo-spatial stimuli and assess the influence of the movement component of the visuo-spatial stimuli on speed perception. Not having road markings in the middle of the road is a common set-up, for example, in rural roads in Germany, where the study was conducted.

Figure 1

Exemplary screenshot of video sequences with red light stimuli and difference in road specifications between Experiment 1A and Experiment 1B of the study.



Note: Participants saw video sequences with red light stimuli on the roadside every 6 m that either remained static or were animated in a way to appear to be moving towards the driver. On the left (A): screenshot of the visual impression of Experiment 1A with reflector posts and road markings. On the right (B): screenshot of the visual impression of Experiment 1B without reflector posts and road markings.

Experiment 1A and Experiment 1B differed in the number of speed levels that participants experienced. However, this is not relevant for the determination of the PSE or differences in the PSE as a function of the independent variable and hence the PSEs are still fully comparable. In Experiment 1A, we used seven different traveling speeds in the test sequences, as five to seven levels are necessary to calculate the PSE properly (Becker-Carus & Wendt, 2017). Traveling speed in the test sequences with static lights varied from 70 km/h to 130 km/h in 10 km/h steps to ensure an adequate range for calculating the PSE (Becker-Carus & Wendt, 2017). The range was scattered around 100 km/h, as traveling speed in the reference sequence was set to 100 km/h. We adjusted the speed levels in the condition with oncoming lights to vary between 50 km/h to 110 km/h, again in 10 km/h steps. We followed this approach based on the simplified idea of the perceived speed to be a result of a linear relation of the actual personal (traveling) speed and the speed in which objects in the environment approach and roll by. We conducted a pretest with three participants for a first indication where the PSE might be located when encountering oncoming lights. The pretest suggested that the PSE would likely be around 80 km/h. Based on this information, we scattered the traveling speeds in the condition with oncoming lights around 80 km/h. This resulted in a range of 50 km/h to 110 km/h to avoid a ceiling effect of the test sequence always being indicated to be “faster” than the test sequence, which would have prevented the possibility to

calculate a PSE. We tested each level of the factor presentation condition (the static lights and the oncoming lights) 20 times for each speed level to have enough answered trials to calculate the PSE. Thus, each participant encountered 280 trials, divided into 10 blocks à 28 trials to allow for breaks if needed.

In Experiment 1B, we used five different traveling speeds in the test sequences. We made this change to Experiment 1A, where we had tested seven different traveling speeds but found that five levels would be sufficient. An uneven number of speed levels was required to have the same number of speeds above and below the speed of the reference sequence. Thus, traveling speed in the test sequences with static lights ranged from 80 km/h to 120 km/h in 10 km/h-steps. As we found the line of argumentation to adjust the speed levels for oncoming lights to avoid a ceiling effect in responses in Experiment 1A to be valid, the speed levels for oncoming lights ranged from 60 km/h to 100 km/h. Table 1 illustrates the tested speed levels in Experiment 1A and Experiment 1B. We tested each level of the factor presentation condition 30 times for each traveling speed, since fewer traveling speeds to be tested allowed for more repetitions of each traveling speed for a similar duration as in Experiment 1A, giving a higher probability to calculate a PSE for each participant. Thus, each participant encountered 150 trials, divided into 5 blocks à 30 trials. The trials were presented randomly across presentation conditions.

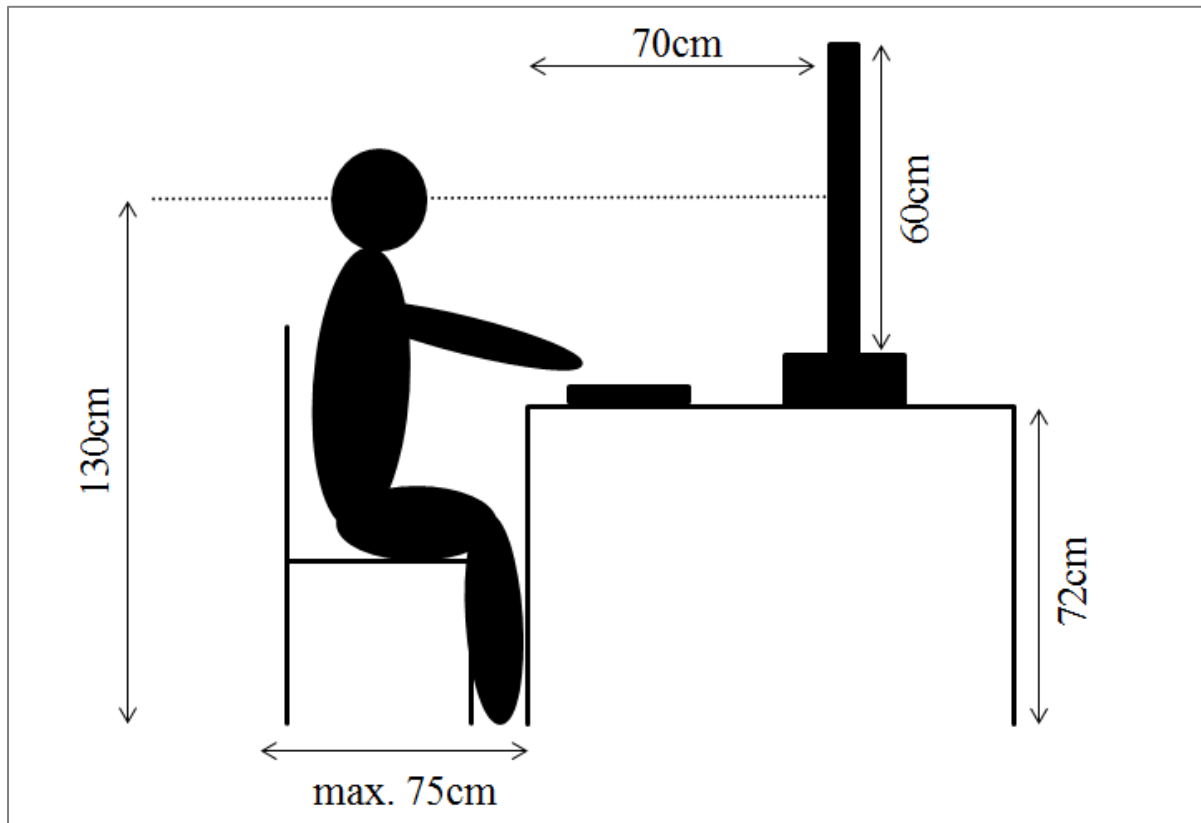
Table 1

Traveling speeds in video sequences for reference and test sequences

Experiment 1A			Experiment 1B		
Reference sequence with-out lights	Test sequence with static lights	Test sequence with oncoming lights	Reference sequence with-out lights	Test sequence with static lights	Test sequence with oncoming lights
100 km/h	70 km/h	50 km/h			
100 km/h	80 km/h	60 km/h	100 km/h	80 km/h	60 km/h
100 km/h	90 km/h	70 km/h	100 km/h	90 km/h	70 km/h
100 km/h	100 km/h	80 km/h	100 km/h	100 km/h	80 km/h
100 km/h	110 km/h	90 km/h	100 km/h	110 km/h	90 km/h
100 km/h	120 km/h	100 km/h	100 km/h	120 km/h	100 km/h
100 km/h	130 km/h	110 km/h			

Note: We tested seven different speed levels in Experiment 1A and five different speed levels in Experiment 1B, since Experiment 1A showed that 5 levels would have been sufficient for calculating the PSE.

We compiled the video material for the tested sequences by recording footage from a driving simulator; the simulation was modeled by Virtual Test Drive 2.1 (by VIRES). VIRES road network editor is based on OpenDRIVE road networks. By using the test mode of Virtual Test Drive 2.1, we simulated a drive in the artificial environment with a constant speed according to the specified 10 km/h-steps between 50 km/h and 130 km/h. We recorded the videos in MP4 format (HD 1080p 25 fps, 1920x1080). Bridges et al. (2020) tested a 60 Hz refresh rate for PsychoPy under Windows and achieved a mean precision in timing of 1 ms. We therefore assumed that PsychoPy can reliably render our 25 Hz videos and would have no problem with 60 Hz videos either. We recorded 3000 milliseconds (ms) long video sequences that showed a section of a country road surrounded by a rural environment with a few trees in the distance (see Figure 1). The duration of 3000 ms was longer than in other comparable studies, which used, for example, video sequences with a duration of 700 ms (Pretto et al., 2012) for the method of constant stimuli. Pilot testing prior to the experiment showed that the condition with oncoming lights required more time than 700 ms to create the impression of a movement. The duration of 3000 ms provided a subjectively good solution to see the movement properly. The condition with static lights was matched to this. The perspective in the video sequences was from the driver's view and contained a fixation cross in the middle of the road on the level of the horizon. We standardized weather and light conditions to a cloudy sky just before dusk to simulate rather low-light conditions to have the red lights appear more prominent, see Figure 1. The video sequences did not contain engine sound or auditory stimuli to prevent any sound-related effects. There was no oncoming traffic to prevent any influence on speed perception. We conducted both experiments in a closed test room at the Institute for Automotive Engineering of RWTH Aachen University, Germany. We blocked out daylight to ensure comparable light conditions. Participants were sitting on a height-adjustable chair in front of a desk on which a 49" screen (Samsung 49" Flat QLED 4k with 60 Hz frame rate) and a standard keyboard were placed in front of them. They adjusted the height of the seat for their eye level to be at the level of the center of the screen (Figure 2) and sat centrally in front of the screen. The distance between the back of the chair and the desk did not exceed 75 cm. This ensured a standardized viewing angle and distance to the screen. We glued small patches of fleece fabric on the relevant keys Y (indicating the first video sequence to be perceived as faster) and M (indicating the second video sequence to be perceived as faster) so that participants could detect and select them easily.

Figure 2*Set-up and dimensions of experimental set-up*

Note: Illustration of the participant sitting on a height-adjustable chair in front of a table holding the keypad and the screen. Heights and distances are illustrated.

We conducted a pre- and post-questionnaire to gather demographic data and additional information whether participants used strategies in the study and if so, which ones (multiple answers possible), and whether they had noticed the lights at all.

Procedure

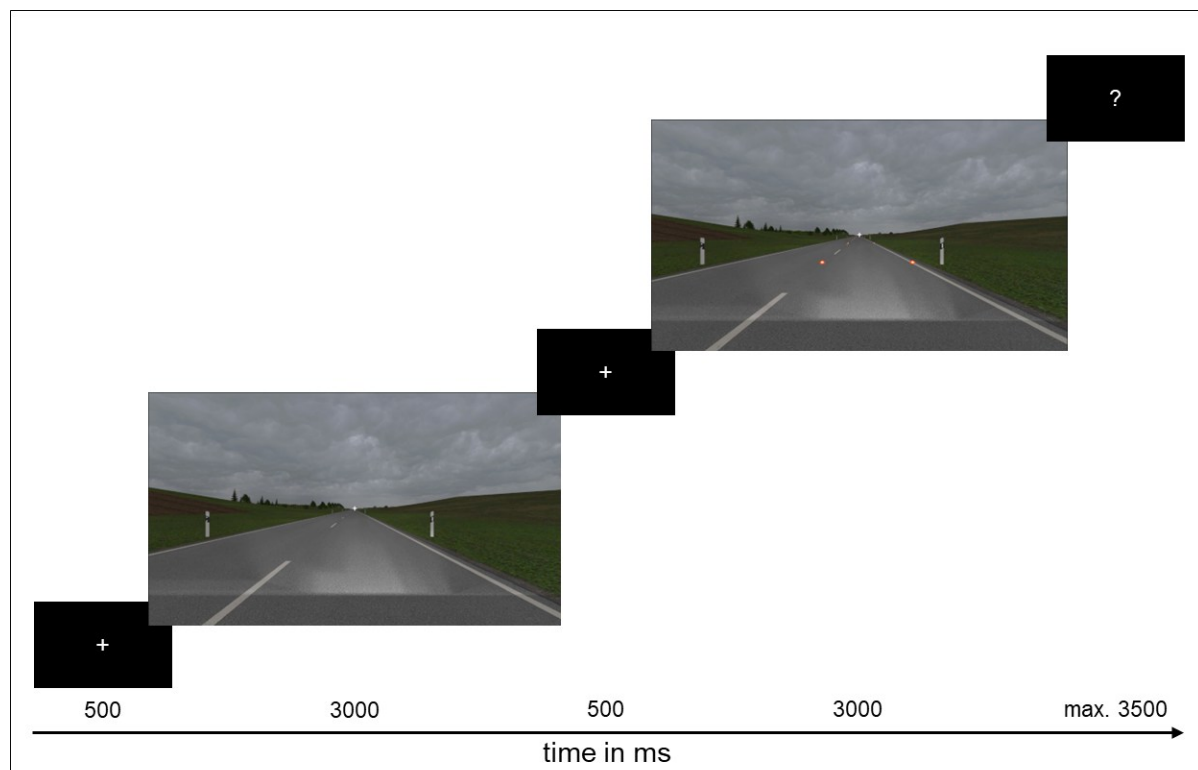
We conducted Experiment 1A in January 2020 and Experiment 1B in July 2021². Participants signed formal documents including giving informed consent to the study and completed a pre-questionnaire. We then asked them to adjust their sitting position and -height according to the specifications and informed participants about the task of the study. Instruction of the task was presented on the screen. We informed participants that they were going to see

² The long period between Experiment 1A and 1B was due to planning and testing difficulties during Covid19. For Experiment 1B, we complied with the local Covid19 regulations in July 2021. Participants were alone in the testing room and were connected to the experimenter via a video-conferencing system. We aligned the camera in the test room in such a way that the experimenter could see the test monitor and the participant from behind via the video conferencing system.

two consecutively presented video sequences in each trial. When a question mark appeared on the screen, they had to rate if they perceived the traveling speed in the first or the second video as faster. We stressed that the decision relied solely on participants' subjective impression, and there were no wrong responses. We set the maximum reaction time to 3500 ms to collect participant's impulsive reactions. If participants did not respond, the next trial started automatically after expiry of the time limit. Figure 3 illustrates the trial sequence.

Figure 3

Trial sequence



Note: Illustration of the trial sequence with 500 ms of a black screen displaying a fixation cross, followed by a 3000 ms-long video sequence (reference sequence or test sequence, depending on the randomization), a 500 ms-long inter-stimulus interval, followed by another 3000 ms-long video sequence (reference sequence or test sequence, depending on the randomization), and a black screen with a question mark to indicate participants to respond, displayed for a maximum duration of 3500 ms. Video sequences in this figure show material from Experiment 1A.

We informed the participants that the decision might be obvious in some trials but more difficult in other trials. In case of doubt, they were encouraged to make an intuitive decision. The reason for this is that the .5 probability level is essential for further analysis of the PSE: If people tended to rather press no key when being indecisive, it would have led to data

loss and therefore problems when trying to determine the PSE. Breaks could be taken as needed between blocks. We told participants to focus on the fixation cross in the center of the screen. After the instruction, participants started with a test block of 10 trials. They were aware that the responses of the test block were not analyzed. To make sure participants fully understood the task, the instructor stayed inside the test room during the test block and answered remaining questions. After doing so, the instructor left the room and reentered when the study was completed. Experiment 1A took about 50 minutes, depending on how long participants' breaks were. Experiment 1B was part of a larger study consisting of two further experimental blocks. Those included auditory stimuli corresponding to the light stimuli and are not part of this paper. This overall study followed a blocked approach to avoid condition order effects within one block. The order of blocks was randomized among the participants, including short breaks before another block started. Blocks were independent from one another. This paper focuses only on the block which replicated Experiment 1A, excluding reflector posts and road markings, to draw a direct comparison. The overall study lasted 75 to 80 minutes, with the block relevant for Experiment 1B taking about one third of the overall time. The study ended with the post-questionnaire and a debriefing about the hypotheses of the experiment.

Design

We based the study on a 2 x 2 mixed design with the within-subjects factor *presentation condition* (2 levels; static lights vs. oncoming lights) and the between-subjects factor *presence of road markings* (2 levels; with road markings and reflector posts vs. without road markings and reflector posts). The dependent variable was the PSE in kilometers per hour (km/h). Significance was tested at $\alpha = .05$.

Results

Data Preparation

To determine the PSE, binary logistic regressions were calculated for the data of both presentation conditions of every participant. We therefore calculated 56 binary logistic regressions for Experiment 1A and 72 binary logistic regressions for Experiment 1B due to the larger sample. We used the respective function with the coefficients α and β to calculate the PSE, which is the .5 probability point of the logistic function (Kim et al., 2014). For this, variable α and β of the respective logistic regression were inserted into the equation. As a prerequisite for calculating the PSE, each binary logistic regression must yield a significant result to

assume a significant prediction between the predictor variable speed and the key response as outcome variable. For this reason, data sets from eight participants in Experiment 1B, with each having at least one non-significant result in one of the two calculated binary logistic regressions, were excluded, resulting in 28 participants for further analysis. We used IBM SPSS Statistics 24.0 for all calculations.

Data Analysis

We conducted a 2 x 2 mixed ANOVA with repeated measures on the within-subjects factor presentation condition (2 levels; static lights vs. oncoming lights) and the between-subjects factor presence of road markings (2 levels; with road markings and reflector posts vs. without road markings and reflector posts). The ANOVA revealed a significant main effect for presentation condition, $F(1,54) = 8.50, p = .005, \eta_p^2 = .14$, a significant main effect for presence of road markings, $F(1,54) = 17.44, p < .001, \eta_p^2 = .24$, and a significant interaction between presentation condition and presence of road markings, $F(1,54) = 8.94, p = .004, \eta_p^2 = .14$.

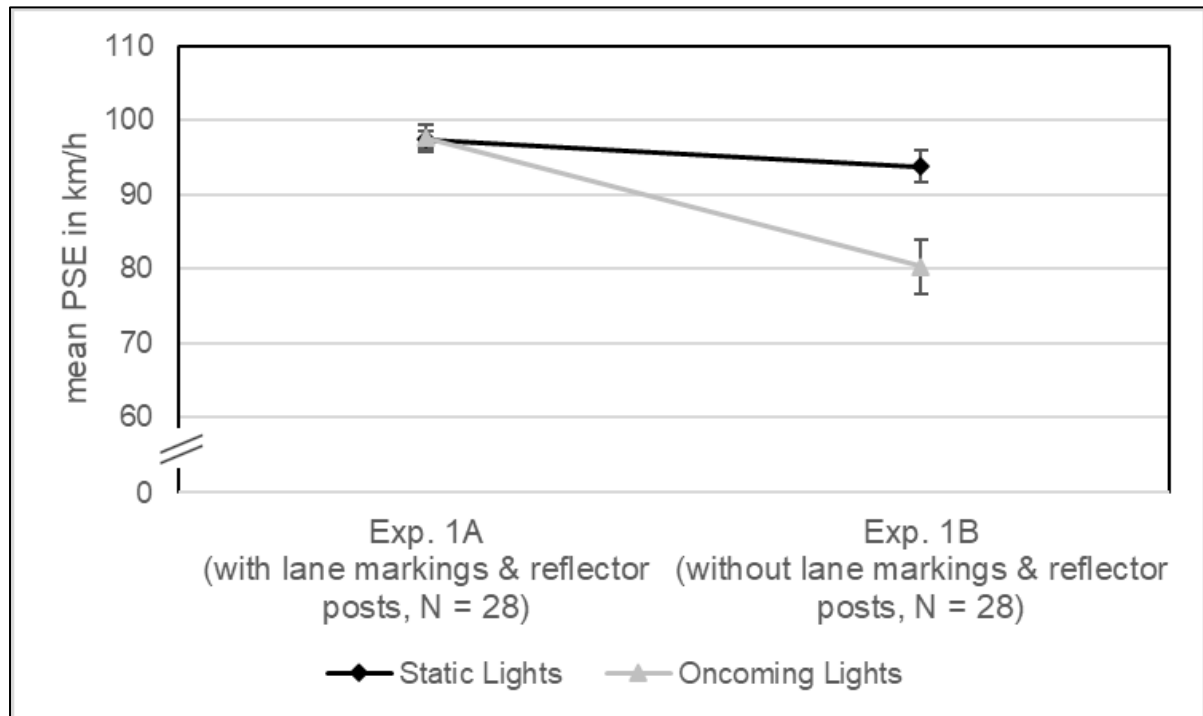
To analyze the interaction effect further, we conducted two separate post-hoc t-tests for paired samples (two-tailed), one for Experiment 1A and one for Experiment 1B. The t-test for Experiment 1A revealed no significant difference between static lights ($M = 97.43$ km/h, $SD = 6.32$ km/h) and oncoming lights ($M = 97.60$ km/h, $SD = 9.36$ km/h), $t(27) = -0.15, p = .879, d_z = 0.03, 95\% \text{ CI } [94.98, 99.88]$. The post hoc t-test for Experiment 1B, however, showed that the PSE of static lights ($M = 93.79$ km/h, $SD = 11.46$ km/h) was significantly higher than the PSE of oncoming lights ($M = 80.32$ km/h, $SD = 19.59$ km/h), $t(27) = 3.05, p = .005, d_z = 0.58, 95\% \text{ CI } [89.35, 98.24]$, see Figure 4.

Results of the post-questionnaire revealed that seventeen participants in Experiment 1A reported to have used the strategy of estimating the traveling speed by counting reflector posts and eight participants said that they had counted the gaps of the road markings in the center of the road (multiple answers possible). Eleven participants in Experiment 1B reported to have used a field on the left side of the road in the simulated environment as a reference to estimate speed and distance driven. Two participants in Experiment 1A and one participant in Experiment 1B mentioned to have counted the seconds of the video sequence. Another strategy used by one participant was to estimate the traveling speed by the distance travelled. One participant in Experiment 1A and one participant in Experiment 1B oriented themselves towards the lights on the sides of the road. One participant in Experiment 1A explained to have tried to find an inner rhythm when watching the video sequence. Four participants in

Experiment 1A and fifteen in Experiment 1B reported to not have used any strategy. Every participant confirmed to have seen the lights when asked.

Figure 4

Mean PSEs (in km/h)



Note: Results for static lights and oncoming lights for Experiment 1A (with lane markings and reflector posts) and Experiment 1B (without lane markings and reflector posts). Error bars indicate standard errors.

Discussion

We conducted Experiment 1A and 1B in a laboratory setting to investigate the effect of visuo-spatial stimuli on speed perception. Our participants encountered a simulated straight road with either static lights or oncoming lights, either with reflector posts and road markings (Experiment 1A) or without road markings (Experiment 1B). We applied the method of constant stimuli (see, e.g., Pretto et al., 2012). Participants had to indicate which traveling speed in two consecutive video sequences they perceived as faster. This led to the calculation of the point of subjective equality (PSE), indicating the speed at which participants perceived the velocity in both video sequences to be the same.

We did not find a difference between static lights and oncoming lights when reflector posts and road markings were present in Experiment 1A, though we expected the oncoming

lights to alter the optic flow (Gibson, 1950; Köhler et al., 2022; Manser & Hancock, 2007). It is possible that drivers did not actively notice the moving component of the lights, even though every participant had seen the lights itself³. However, most participants reported to have counted either reflector posts or gaps between road markings. According to Lidestam et al. (2019), this is being taught in some driving lessons to estimate speed and could have influenced our results: All participants reported to have seen the lights and the majority mentioned the movement component. It is therefore possible that those participants who reported to have used this strategy based their responses on their counting strategy alone. It is also possible that actively driving, as participants did in the field test of the study by Köhler et al. (2022), instead of the passive task of watching video sequences could have prevented the use of this strategy due to limited resources. This could be subject to future investigation.

However, we found a significant interaction between presentation condition and presence of road markings, suggesting that perceived speed differed between Experiment 1A and Experiment 1B regarding the two tested presentation conditions, static and oncoming lights. While we did not find a difference between oncoming and static lights when road markings were present in Experiment 1A, post hoc t-tests revealed a significantly lower PSE for oncoming lights than for static lights when road markings and reflector posts were not part of the experimental setting in Experiment 1B. This significant difference between static and oncoming lights in Experiment 1B was 13 km/h, which is considerably more than in Experiment 1A. Due to the significant interaction, we can assume that this difference was significantly bigger in Experiment 1B than in Experiment 1A. Using road markings and reflector posts to estimate speed was likely a well-learned process (Theeuwes, 2021), on which drivers relied in Experiment 1A. When these were not present, drivers relied on other sources of information to estimate their traveling speed, which were the lights on the side of the road.

Interestingly, lights on the side of the road led to a clear difference in perceived speed but had no influence when they were overruled by other processes such as counting reflector posts, as presumably in Experiment 1A. Lidestam et al. (2019) categorized processing of speed-related visuo-spatial information into energy- and rhythm-based processing. When a vehicle moves at a higher speed in the visual field, it has a higher energy. This is described as energy-based processing. This is like the optic flow described by Gibson (1950). However,

³ We investigated whether red lights by themselves might have an influence in a pre-study (not reported) with 27 participants, comparing red static lights with the same specifications as in Study 1 to a baseline of video sequences without lights in the driving environment. We did not find a significant difference of PSEs, suggesting that red lights per se did not influence speed perception in our experimental setting.

continuously placed objects like road markings or reflector posts create a rhythm when driving. The frequency of this rhythm is higher at greater velocities and lower when driving at lower speeds. Lidestam et al. (2019) described rhythm-based processing as more dominant than energy-based processing, and as a result, human speed perception would be likely to rely on the rhythm of distinct objects in the field of view. Therefore, when there are stimuli located closely to the participants, it is more likely that participants perceive speed based on these objects in a rhythm-based manner. This would require some amount of cognitive processing. Consequently, counting reflector posts is likely a process explicitly requiring attention (see Cavanagh, 1992; Lidestam et al., 2019). If participants prioritized the counting of reflector posts or road markings, they allocated more resources to this task. It is possible that the task demands for this were high, resulting in a high workload, which would not have allowed participants to process the visuo-spatial stimuli in the form of red lights (Stapel et al., 2019). Furthermore, it could be examined further which factors influence drivers speed perception towards a more energy-based processing and which towards a more rhythm-based processing. If lights were, for example, spaced similarly to the reflector posts or the road markings, this could draw upon the same explicit cognitive processing as counting reflector posts and might lead to a greater focus on the light stimuli. To examine whether participants would still apply this technique in more naturalistic environments with more and different stimuli, future studies could determine the influence of the lights when different stimuli allowing for rhythm-based processing are present. Also, future research could gradually add more distractors to the experimental setup to determine the exact influence of such distractors on speed perception. Nevertheless, visual information has been reported to be the primary source of information in driving (Macadam, 2003) and thus limits processing of other input (e.g., Posner et al., 1976). Speed-related information is thus likely processed automatically. While the experimental task of comparing the traveling speed in video sequences could technically have been accomplished without the light, our results suggest that they are still being considered, especially in the absence of additional speed-relevant stimuli. These additional stimuli are such strong predictors of speed that additional information, such as the light stimuli in our study, have little further effect on the perception of traveling speed. However, salient stimuli capture automatic attention even if their information is nominally irrelevant (see, e.g., Lange-Malecki & Treue, 2012). The light stimuli in our study are therefore suitable for quasi-subliminal manipulation in speed perception, which can be more efficient than a mere warning sign (see, e.g., Köhler et al., 2022).

The results provide further insights into potentially underlying perceptual reasons in the countermeasure to speeding developed by Köhler et al. (2022), where the light stimuli of our laboratory study were applied in a field test. While both oncoming and static lights led to lower driving speeds in comparison to a baseline without lights, there was no difference between static and oncoming lights (Köhler et al., 2022). This could have come about due to the warning character of the lights in general (Kahneman, 1973), independent from a movement component. The movement component of oncoming lights might have been overruled by attention to other stimuli in the driving environment. More specifically, problems in information processing especially arise when processes interfere, as human information processing is limited due to crosstalk phenomena (see Koch et al., 2018). The results of the present study suggest that driver's attention in the field test by Köhler et al. (2022) was occupied with other stimuli. Drivers are therefore unlikely to base their speed estimation on stimuli aiming at influencing the optic flow when other stimuli for this purpose are present.

In the present study, we tested the influence of visuo-spatial stimuli on human speed perception, because we regarded driving as a spatial control task (see Gibson, 1950; Manser & Hancock, 2007). This paper focused on the input of visual stimuli on speed perception based on an applied measure described by Köhler et al. (2022), who already implemented such a solution in the field. However, according to the theory of directed attention, auditory stimuli are described to attract attention more quickly than visual stimuli (see Aschersleben & Bertelson, 2003; Lukas et al., 2010; Lukas et al., 2014). This leaves the question to what extent auditory stimuli play a role in human speed perception as well. In a laboratory test, people who heard more of their car's engine noise chose to drive slower (Horswill & McKenna, 1999). What remains open, however, is if there might be an acoustic flow (see Pretto & Chatziastros, 2006) when passing objects on the driving environment, similar to the optic flow (Gibson, 1950; Manser & Hancock, 2007; Köhler et al., 2022; Palmisano, 2002).

Note that there are also limitations to our findings and the practical conclusions we wish to draw from them. Firstly, the effect of experiencing slower traveling speeds with oncoming lights in the absence of road markings and reflector posts could have been the result of further learned patterns. Not having lane markings and reflector posts could have been associated with more inhabited surroundings, leading to the expectation of slower movement, as the environment likely influences driving speed (Dumbaugh et al., 2020). Charlton et al. (2010) removed lane markings and adjusted landscaping to mark local roads in a study on self-explaining roads, which led to lower driving speeds. However, this seems unlikely for our study as there were no further cues that could have led to this assumption.

Secondly, speed perception could also be influenced by the field of view, both vertically and in the periphery. According to Lidestam et al. (2019), the bigger the field of view, the slower the chosen driving speed of participants. We placed the participants in our study quite closely in front of a 49" screen to create some peripheral vision of the experimental stimuli. It is possible that a curved screen would be more suitable to create a higher immersion.

Thirdly, the difference in displayed speed levels to calculate the PSE between Experiment 1A (7 levels) and Experiment 1B (5 levels) could have influenced the results. However, this is unlikely, as the number of levels increases the likelihood to be able to calculate a PSE at all, not where the PSE would be located. Furthermore, one could argue that the speed levels between static lights (70 km/h-130 km/h in Experiment 1A, 80 km/h-120 km/h in Experiment 1B) and oncoming lights (80 km/h-120 km/h in Experiment 1A, 60 km/h-110 km/h in Experiment 1B) might not have been fully comparable. However, the assumption behind this was that the PSE within one level of the factor presentation condition (static lights vs. oncoming lights) is always located in the same spot: The PSE shows where two sequences are perceived as equal. Both static and oncoming lights were compared to the same reference sequence. So even if we had tested speed levels between 70 km/h and 130 km/h for oncoming lights as we had for static lights, we would expect the PSE to be the same because the reference sequence and the test sequence would be perceived as equally fast at the same speed for oncoming lights than when testing speed levels between 50 km/h and 110 km/h. However, we wanted to ensure that the traveling speeds we chose would be scattered around the actual PSE. Since we expected the PSE to be lower with oncoming lights, we chose lower driving speeds based on our pretest. This assumption proved to be correct when we found an influence of the oncoming lights on the subjectively perceived traveling speed in Experiment 1B. Here, the PSE for oncoming lights was at 80.32 km/h, which was exactly in the middle of the five provided speed levels. Furthermore, the same speed levels for static and oncoming lights could have led to a virtually perceived imbalance for oncoming stimuli: If our participants had always seen video sequences that they perceived as faster than the reference sequence, they might have felt the need to balance their responses of "faster" or "slower" more. In adjusting the speed levels for test sequences for oncoming lights, we aimed at moderating this potential bias.

Further, placing the lights on the level of the road surface could have been unfamiliar to drivers, as lights are rather placed on delineators or roadside barriers in the driving context than on the ground. It remains open whether placing the lights on the level of delineators

would have had a similar effect. However, we would assume the height to be irrelevant, as we saw an effect of the optic flow on the ground level, which is even further away from the focal point. It is therefore likely to find the same effect at a higher position. Another potential limitation could be the different durations of the two studies as Experiment 1B was part of a larger experiment and participants could have experienced fatigue because of spending so much time with the rather repetitive experimental task requiring constant attention. However, we found the significant difference between static lights and oncoming lights in the longer overall experiment. It is therefore unlikely that fatigue affected our results substantially.

Further, while we aimed at comparable samples for Experiment 1A and Experiment 1B and achieved this especially in terms of gender distribution and mean age, we cannot exclude a potential influence of sample differences. Two participants in Experiment 1B did not hold a driver's license and one person held it for 44 years, leading to a higher standard deviation for the sample of Experiment 1B. After not finding any extreme values in their results, we decided to keep them in the sample, since the experimental task did not include driving itself, but referred to the mere perception of traveling speed, which does not necessarily require active driving experience in a car. However, it is still possible that these sample differences might have had an influence on the results. Future studies could determine the role of driving experience in speed perception, especially since driving experience and expertise in certain tasks have been reported to be qualitatively different when it comes to driving (for an overview, see Pammer & Blink, 2018).

Lastly, our study was conducted under laboratory conditions. While this allows control of potentially confounding variables, it is also not a natural driving situation. Nevertheless, knowledge on the role of different perceptual cues in speed perception can support the development of innovative interventions that aim at enhancing traffic safety and should be investigated further to determine their influence in naturalistic traffic as well.

The findings in this study would allow further application of the tested measure in naturalistic traffic, as done by Köhler et al. (2022). Furthermore, this measure could present an interesting in-car application, for example, by using a head-up display to project such light applications on the road via augmented reality or by animations of ambilight to mimic the optic flow inside the vehicle. However, both applications would require further investigation especially in terms of driver distraction, since applications inside the vehicle must not distract from the driving task or be visually entertaining (European Commission, 2008).

Conclusion

This paper investigated the effect of visuo-spatial stimuli in the form of red lights on drivers' speed perception based on a countermeasure to speeding developed by Köhler et al. (2022) in two experiments. We found that visuo-spatial stimuli in the form of oncoming lights led to a higher perceived traveling speed than static lights, but only when further visual stimuli such as reflector posts and road markings were removed. Active processes such as counting other stimuli might overrule the automatic processing of the light stimuli. Future research should investigate whether speed perception in the traffic context is a mainly visual task or whether auditory information could have an influence on speed perception as well.

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Author contributions

Anna-Lena Köhler conceptualized the studies including methodology, supported in data collection, conducted the formal analysis and interpretation, wrote the original draft including visualization, and administered the overall project. Maren Klatt substantially contributed to the methodological conceptualization and the formal analysis and acquired the data. Iring Koch and Stefan Ladwig validated the conceptualization and methodology, substantially contributed to the interpretation of the data, supervised the studies, and reviewed and edited the original draft. All authors have read and approved the submitted version.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

We based the specifications of the studies reported in this paper on the declaration of Helsinki and the guidelines of the Institute for Automotive Engineering of RWTH Aachen University. Based on these and since we did not conduct any clinical trials, there was no need for ethical approval. The studies were performed on a standard desk with a screen and keyboard and no other risks than required for a regular office job. Regardless, participants gave

their fully informed consent before participating in the study. This included information on and consent to data protection guidelines (according to GDPR of the European Union) and the right to stop their participation anytime without having to give a reason for this and without fearing any consequences. Information on the experiment's hypotheses, which could not be given before participation for methodological reasons, was given to participants in a debriefing after participation.

Consent for Publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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**Investigating the Role of Visual and Corresponding Auditory Stimuli in Driving-Related
Speed Perception**

Anna-Lena Köhler¹ *, Iring Koch², and Stefan Ladwig¹

¹ Institute for Automotive Engineering (ika)
RWTH Aachen University
Aachen, Germany

² Institute for Psychology
RWTH Aachen University
Aachen, Germany

*anna-lena.koehler@rwth-aachen.de

Abstract

Speeding is a main risk factor in traffic. Because drivers need to integrate a variety of information, investigating different perceptual modalities in speed perception can help develop interventions to mitigate speeding. Humans perceive traveling speed relative to the speed of the environment, which is also called “optic flow”. In spatial tasks, processing visual input often dominates processing of auditory input, but simultaneous presentation of information in both modalities can lead to intersensory bias. In the present study, we investigated such cross-modal interactions between visual and auditory information on a simulated road in two experiments (Experiment 1A and 1B). We applied the method of constant stimuli to assess speed perception. Participants were presented with short video sequences and decided via keypress which sequence they perceived as faster, so that it was possible to calculate the point of subjective equality (PSE). Stimuli were either unimodal visual (regular lights on both sides of the road on the asphalt) or bimodal visual-auditory (the same lights and added wind noise every time a light was passed), both either in static positions or animated in a way to give the impression of moving towards drivers. Both experiments showed that oncoming stimuli led to higher perceived speed (indicated by a lower PSE) than static stimuli. However, this influence on perceived speed was stronger in the bimodal visual and auditory than in the unimodal visual condition, suggesting the added influence of acoustic flow on the existing influence of optic flow. In sum, these findings suggest that earlier studies with unimodal visual stimuli underestimated the influence of oncoming stimuli on perceived speed and thus its potential role on mitigating speeding in traffic.

Keywords: *speed perception, optic flow, acoustic flow, traffic safety*

1. Introduction

Driving too fast remains a major cause for car crashes in the European Union (European Commission, 2024), 39.136 crashes in 2023 caused by driver misconduct were attributable to inappropriate speed (Federal Statistical Office, 2024). Even slightly increased driving speeds increased crash rates, making speeding a major safety issue (e.g., Quddus, 2013). Drivers are likely to adopt behavior that is inappropriate for the respective traffic situation, which was found in preparation of developing countermeasures for speeding for drivers and cyclists (among others: Karlsson et al., 2017). Drivers may not always be aware of unsafe driving, as this safety assessment may often be rather a gradual development outside of the driver's awareness (see Kuiken & Twisk, 2001, for a review). For example, results in a study where participants had to estimate distances suggested an unstable relationship between objectively driven speed and subjective speed perception (Wu et al. 2004; see also Denton, 1980, 2007). Understanding the relationship between objective speed and subjective perception can support the targeted development of countermeasures against speeding. However, research on perceptual factors in speed selection has been rather limited (Nash et al., 2016) and focuses on an area of interventions against speeding that is different from, for example, research assessing the impact of penalties for speeding on crash rates (e.g., Baxhuku et al., 2023). Driving essentially requires multitasking performance. For example, longitudinal tracking is apparently one core task executed while driving (Papakostopoulos et al., 2017) and different perceptual information needs to be processed and integrated to execute the driving task (e.g., Köhler et al., 2022). Hence, driving requires both selective and divided attention. Therefore, drivers need to allocate resources to meet task demands, which vary in correspondence with the complexity of the driving task or traffic situation (e.g., Stapel et al., 2019). According to multiple-resource theory (see e.g., Wickens, 2008), tasks can be executed in parallel with only little resource competition when they are processed at different processing stages (i.e., perception, decision/response selection, motor execution), processing codes (i.e., spatial vs. verbal), perceptual modality (auditory vs. visual), and motor modalities (manual vs. vocal). However, the factors influencing the degree of interference in such multitasking situations and the cognitive mechanisms underlying the resolution of such interference are still under debate (see Koch et al., 2018, for an extensive review of human multitasking performance in speeded tasks). It is therefore necessary to understand the role of different perceptual input modalities and their interaction when presented simultaneously in speed perception during driving.

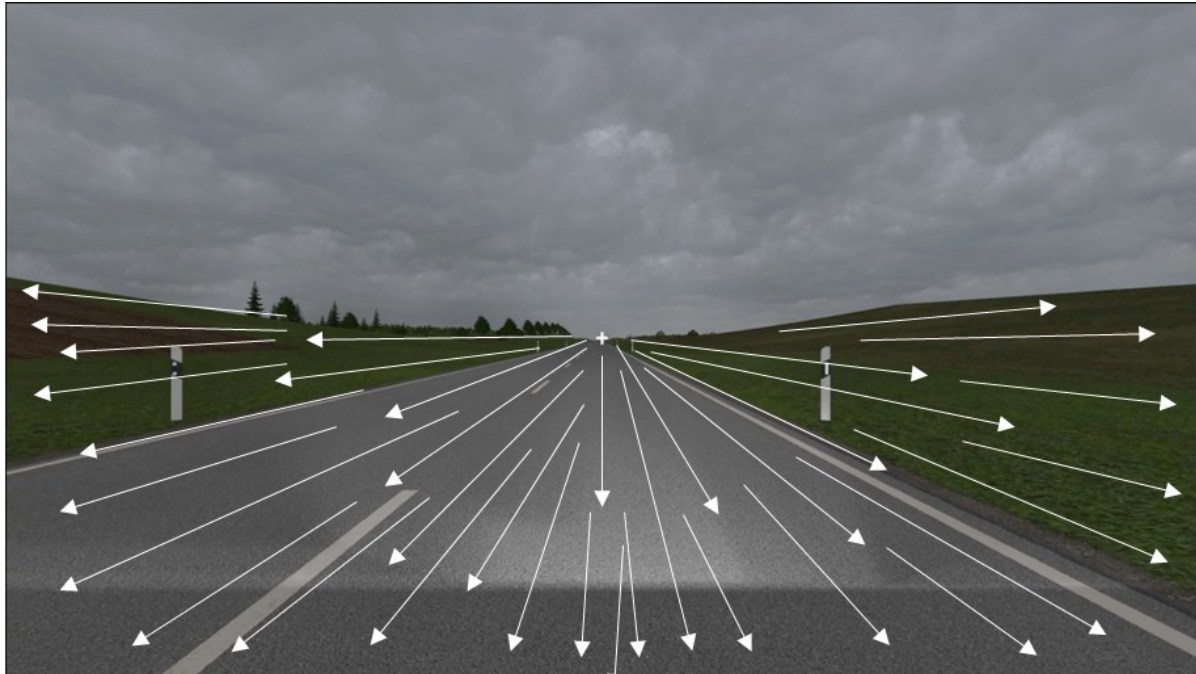
Many countermeasures against speeding focus on providing drivers with negative feedback for speeding behavior, which can be the classical speeding ticket or an uncomfortable consequence when, for example, driving too fast over a speed hump on the road aiming at slowing drivers down. (French, 2011; for an overview see Karlsson et al., 2017). The Safe System approach, on the other hand, focuses on creating an environment where behaving safely is the easiest option (World Health Organization, 2017, 2023). An understanding of perceptual factors influencing speed perception can aid the development of countermeasures against speeding that support the Safe System approach. Theeuwes (2021) reviewed findings with respect to the concept of self-explaining roads, on which drivers should automatically know how to behave appropriately. For example, drivers were able to identify local roads more easily when these did not have road markings and when spaces around the roads were subject to more landscaping, indicating a more inhabited area, leading to lower speed levels (Charlton et al., 2010). Various researchers aimed at influencing driving speed by placing objects in the traffic surroundings. On the one hand, this was tested in natural driving environments, for example with lights on two sides of a road (Köhler et al., 2022), transverse road markings (Bergh Alvergren et al., 2019; Ding et al., 2020; Gates et al., 2008), or stripes with spaces between them decreasing more and more on the asphalt (Thaler & Sunstein, 2008) or on tunnel walls (Manser & Hancock, 2007). The findings of these studies revealed that drivers drove more slowly in response to activated light spots on the sides of the road (Köhler et al., 2022) and also in response to any kind of markings on the road (Bergh Alvergren et al., 2019; Ding et al., 2020; Gates et al., 2008; Thaler & Sunstein, 2008) or on tunnel walls (Manser & Hancock, 2007). On the other hand, driving speed was tested also in the laboratory, for example, by assessing the influence of lights not only on driving speed (Köhler et al., 2022) but also on perception of traveling speed (Köhler et al., 2023), or the influence of abstract patterns before a neutral background on own driving speed (Palmisano, 2002). Results suggested that stimuli in the driving environment could influence driving speed (Gates et al., 2008; Köhler et al., 2022; Manser & Hancock, 2007) and the passing of objects could influence the perception of the driver's own speed (Köhler et al., 2023; Palmisano, 2002).

Visual input is likely to play a crucial role in driving, as drivers need to see and assess their surroundings to navigate in traffic. Humans likely perceive their own driving or traveling speed relative to the speed of the environment (Palmisano, 2002; Pretto & Chatziastros, 2006). This is in line with the optic flow (Gibson, 1950), which is created by passing objects in the environment, for example derived from the self-motion of a car (Higuchi et al., 2020). Stimuli in the driving environment pass the vehicle and therefore create a feeling of self-

motion. Pretto and Chatziastros (2006) found in a simulator study that drivers drove slower when optic flow was increased, for example by additional stimuli added to the driving environment than without this added visual information. Figure 1 illustrates the optic flow principle.

Figure 1

Illustration of the optic flow paradigm based on Higuchi et al. (2020).



Köhler et al. (2022) developed an intervention to encourage drivers to adopt a safer speed via the infrastructure and applied it in a naturalistic driving setting. They conducted one laboratory study in a driving simulator and one study in real traffic with over 1,000 participants. They found that adding visual stimuli in the form of red lights to both sides of a motorway exit influenced speed adaptation. When detecting a speeding driver, a computer system activated light spots that were either animated in a way to create the impression to be moving toward the driver or were activated without a movement component. By not displaying the light spots permanently, the intervention aimed at preventing habituation (see, e.g., Gates et al., 2008; Hautzinger et al., 2011). Both ways of activating the lights led to lower driving speeds. A follow-up study investigated the effect of these light stimuli on speed perception further and found that adding oncoming visual stimuli in the form of simulated red lights likely especially influenced subjective speed perception. This could only be found when participants had no further information such as reflector posts or road markings to base

their assumption about their speed on (Köhler et al., 2023). These findings demonstrate the high degree to which driving-related speed perception is governed by processing of visual stimuli. The present study goes an important step further and focuses not only on visual stimuli, but examined the influence of auditory stimuli and their interaction with these visual stimuli.

These previous studies, including the studies by Köhler et al. (2022, 2023), focused exclusively on visual stimuli. However, visual stimuli alone may be an insufficient source of information for drivers (Papakostopoulos et al., 2017). A variety of studies in laboratory conditions found that auditory stimuli attracted attention more quickly (Aschersleben & Bertelson, 2003; Lukas et al., 2014; Shams et al., 2002). Further, auditory information decreased the processing weight of visual information in temporal discrimination tasks when the two sources of information were in conflict in a variety of studies (temporal ventriloquism, e.g., Morein-Zamir et al., 2003, see also Manabe & Riquimaroux, 2000; Shams et al., 2002, 2004) and reinforced the visual modality when information in both modalities corresponded (Calabro et al., 2011; Gagliano, 2016; Keshavarz et al., 2014; Ramkhalawansingh et al., 2016; Recanzone, 2003), leading to lower error rates compared to non-corresponding bimodal stimuli presentation (Minakata & Gondan, 2018) and unimodal stimulus presentation (Diederich & Colonius, 2004; Stefanics et al., 2005). Sounds such as wind noise or tires on the asphalt can influence speed perception (for an overview see Fischer et al., 2012). A driving simulator study by Denjean et al. (2012) revealed that participants not only underestimated their speed in general but drove especially fast without engine noise. It is therefore possible that corresponding auditory information could create an acoustic flow (Pretto & Chatziastros, 2006), comparable to the optic flow (Gibson, 1950; Köhler et al., 2022; Köhler et al., 2023; & Palmisano, 2002). Hence, both the visual and auditory modality may have relevance to speed perception.

Different perceptual sources contribute to the overall background noise that constitutes the auditory feedback when driving, such as engine and tire noise, or environmental sounds, wind, or air noise (Denjean et al., 2012; Fischer et al., 2012). Auditory cues intensify the effect of visually induced self-motion illusion, also referred to asvection (e.g., Gagliano, 2016; Keshavarz et al., 2014). Applied to driving, corresponding visual and auditory information led to a reduction in speed variability compared to visual information alone, suggesting that bimodal corresponding information results in a more accurate speed estimation and thus supports a more accurate speed perception (Ramkhalawansingh et al., 2016). Therefore, our paper targeted not only visual information but also examined the influence of auditory

information and especially combined visual and auditory information on speed perception. We deemed it necessary to measure this influence the same way as the influence of only visual information on speed perception is measured to draw direct conclusions on the influence of the respective modalities on speed perception.

Köhler et al. (2023) examined the effect of unimodal visual stimuli on driver's speed perception in short video sequences of 3000 ms duration and found that subjectively perceived traveling speed with oncoming stimuli was higher than with static lights, in line with the optic flow paradigm (e.g., Palmisano, 2002). The present study builds on this previous work and aims at investigating the added influence of auditory stimuli on speed perception. Like the optic flow could be altered by visual stimuli when passing the light stimuli in the study by Köhler et al. (2023), auditory stimuli can potentially alter acoustic flow (Pretto & Chatziastros, 2006). To determine the influence of auditory information on speed perception, we used auditory stimuli in the form of wind noise when passing a light. When comparing the influence of unimodal visual stimuli on speed perception with the influence of bimodal stimuli (corresponding visual and acoustic) on speed perception, we expected the bimodal combination of visual and auditory information to lead to a more accurately perceived traveling speed, as auditory information could intensify the visual information (e.g., Gagliano, 2016; Keshavarz et al., 2014). In summary, the present study investigated the influence of auditory stimuli and combined auditory and visual stimuli on speed perception, while previous studies on (optic) flow related information in the traffic context focused on unimodal visual stimuli.

We applied the method of constant stimuli (Laming & Laming, 1992; Pretto et al., 2012) to test our hypotheses. For this, various reference stimuli, in our case a video sequence of driving on a rural road without light stimuli, and test stimuli, in our case three different (video) sequences of driving on a rural road with different light stimuli (unimodal-vis, bimodal-vis+aud, & unimodal-vis), are presented to the participant. The reference sequence remains constant throughout the experiment. The participant then decides via key press in which of the two video sequences they perceived the traveling speed as faster. This dichotomous response is the basis for the calculation of a binary logistic regression for every independent variable and participant, leading to the calculation of the point of subjective equality (PSE), which is the .5 probability point for an observer to choose any option arbitrarily because they appear subjectively the same (Kim et al., 2014). This represents the perceived traveling speed (Kim et al., 2014). The lower the PSE, the higher the perceived traveling speed (see also Köhler et al., 2023).

2. Experiment 1A

We conducted two experiments in a laboratory setting (Experiment 1A and 1B). The unimodal-vis presentation modality in Experiment 1A did not contain engine sound for comparability of the same condition with the publication by Köhler et al. (2023). We added engine sound to the unimodal-vis presentation modality in Experiment 1B for better comparability with the bimodal-vis+aud presentation modality, which included engine sound in both experiments.

2.1 Method

2.1.1 Apparatus, Task, and Stimuli

We programmed the experiment on PsychoPy version 2021.2.0 (Peirce et al., 2019) and ran it on Windows10. In line with Köhler et al. (2023), participants were presented with two video sequences per trial, a reference sequence and a test sequence. One half of the participants saw the reference sequence as the first video sequence of each trial, the other half the test sequence (counterbalanced). The reference sequence was a video sequence without lights, wind, or engine sound. While the reference sequence remained the same over all trials, the test sequence varied in tested stimulus dynamics, driven speed, and auditory information, which we explain in the following.

The experiment comprised of three variations of the factor presentation modality (see Table 1 for an overview), unimodal visual stimuli (unimodal-vis), corresponding bimodal (visual and acoustic, bimodal-vis+aud) stimuli, and unimodal auditory stimuli (unimodal-aud) serving as a manipulation check. The order was counterbalanced across participants. The unimodal-vis presentation modality displayed visuospatial stimuli. Participants encountered short video sequences with either statically illuminated simulated red light stimuli or simulated light stimuli animated to create the impression of moving toward the driver at a speed of 50 km/h. In Experiment 1A, we did not include engine sound in the unimodal-vis presentation modality to replicate the study by Köhler et al. (2023). In the bimodal-vis+aud presentation modality, participants encountered the same visual light stimuli enhanced with acoustic information, engine sound and overlaid wind noise. Each light was accompanied by a short sound giving the impression as if the lights had air resistance (wind noise). For both variations of the factor presentation modality including visuospatial stimuli, we placed stimuli every 6 m to match the conditions of the studies by Köhler et al. (2022) and Köhler et al. (2023). In the unimodal-aud presentation modality, participants encountered the same

auditory information as in the bimodal-vis+aud presentation modality but without seeing the visual information with the visuospatial stimuli. This was a manipulation check only because seeing the road is obviously imperative for driving. Hence, this has a low ecological validity and simply assessed the pure effect of auditory information on speed perception.

Table 1

Overview over the variation of presentation modalities of Experiment 1A.

Presentation Modality	Visuo-spatial	Auditory
unimodal-vis	Static and oncoming red lights every 6m	no wind noise, no engine sound
bimodal-vis+aud	Static and oncoming red lights every 6m	corresponding wind noise when passing a light, speed-specific engine sound
unimodal-aud (manipulation check)	no video (black screen with fixation cross)	corresponding wind noise when passing a light, speed-specific engine sound

Note: The order of presentation modality was counterbalanced across participants.

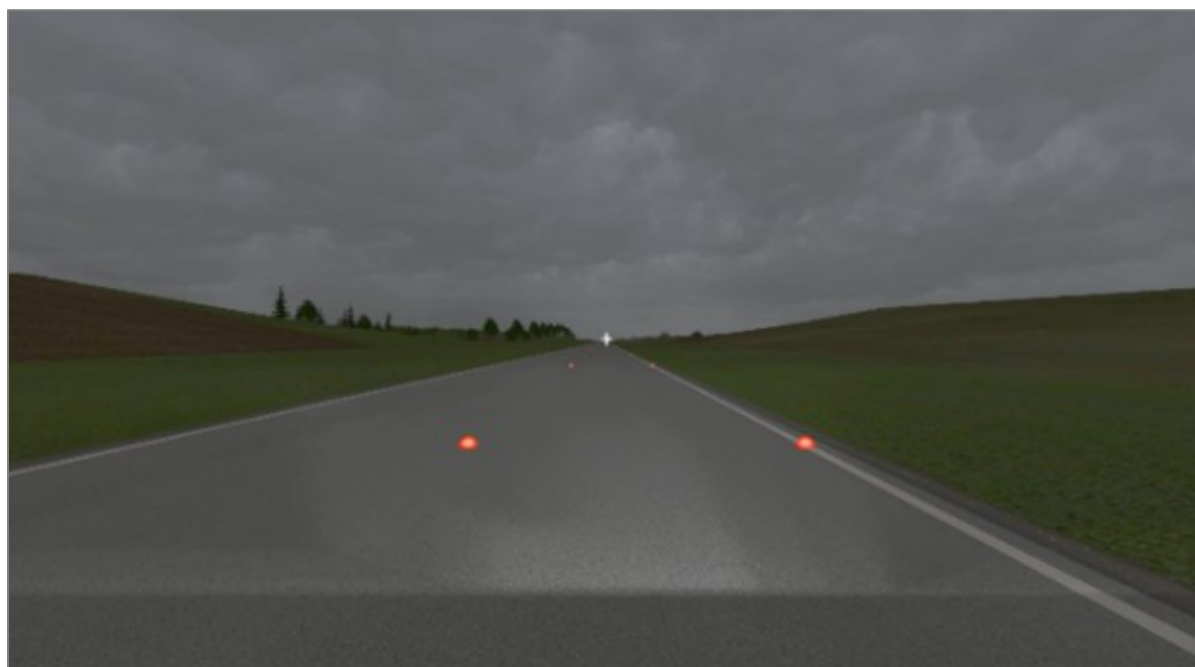
We used five different traveling speeds in the test sequences. Five to seven levels are necessary to calculate the PSE (Becker-Carus & Wendt, 2017) and five levels were previously shown to be sufficient when testing for the influence of visuospatial stimuli (i.e., without auditory information) on speed perception (Köhler et al., 2023). Traveling speed in the test sequences with static stimuli ranged from 80 km/h to 120 km/h in steps of 10 km/h for an adequate range for further calculation of the PSE (Becker-Carus & Wendt, 2017). The range was scattered around 100 km/h, because the reference sequence was set to 100 km/h. In test sequences with oncoming stimuli, the speed varied between 60 km/h and 100 km/h in 10 km/h steps. In line with Köhler et al. (2023), we wanted to avoid a ceiling effect when assuming a linear influence of the oncoming stimuli at a speed of 50 km/h. As this approach proved to be successful in the studies by Köhler et al. (2023), we applied it for this study as well.

We compiled the video material for the tested sequences by recording footage from a driving simulator. The simulation was modeled by Virtual Test Drive 2.1 (by VIREs). VIREs road network editor is based on OpenDRIVE road networks. We used the test mode of Virtual Test Drive 2.1 and simulated a drive in the artificial environment with a constant speed

according to the aforementioned speed levels. Videos were recorded in MP4 format (HD 1080p 25 fps, 1920x1080). Bridges et al. (2020) tested a 60 Hz refresh rate for PsychoPy under Windows and achieved a mean precision in timing of 1 ms. We therefore assumed that PsychoPy can reliably render our 25 Hz videos and would have no problem with 60 Hz videos either. Video material consisted of 3000 ms video sequences showing a section of country road (see Figure 2, as in Köhler et al., 2023). Perspective was from the driver's view with a fixation cross in the middle of the own driving lane on the level of the horizon. We standardized weather and ambient conditions to a cloudy sky to simulate low-light conditions, making the red lights appear more prominent. There was no opposing traffic and no road markings or reflector posts to isolate the effect of the experimental stimuli on speed perception. The starting point on the road was always the same.

Figure 2

Exemplary screenshot of video sequences with red light stimuli and fixation cross.



Note: Participants saw moving video sequences with red light stimuli on the roadside every 6 m that either remained static or were animated in a way that appear to be moving toward the driver.

The presentation modalities bimodal-vis+aud and unimodal-aud included acoustic information. The first acoustic information was the engine sound while driving at the speed of the corresponding visual sequences. The engine sound for Experiment 1A was recorded binaurally, aurally compensated, and calibrated (BHS II from Head Acoustics) while driving a Seat Leon ST FR TDI (2019) with 110 kW and 7 gear DSG. Measurements were recorded on

a two-lane highway in Germany in March 2021 in dry conditions. The measurement data included only the interior noise without ventilation. No overtaking maneuvers were performed. We activated cruise control. The gear was selected by the automatic transmission.

Secondly, we added auditory stimuli sounding like overlaid air resistance noise to the visual stimuli. This was in addition to the engine sound. We used edited brown noise via Audacity® (version 2.4.2). Brown noise covers strengthened lower frequencies (Azizi & Yazdi, 2019), thus simulating air or wind noise best (Ramkhalawansingh et al., 2016). Enhancing the illusion of air resistance noise rushing by, we integrated volume and frequency shifts simulating the *Doppler Effect*, a change in perceived frequency due to motion (Toman, 1984). As binaural stimulus presentation and a frequency shift as the Doppler Effect enhance the illusion of motion (Kapralos et al., 2004), we implemented both aspects.

We determined the sampling rate of the air resistance noise in a pretest ($N = 11$). Participants were told that the audio track simulated the soundscape while sitting in a vehicle and driving past objects, for example, trees, at regular intervals. They ranked six different sampling rates ranging from 1000 Hz to 8000 Hz regarding their perceived accuracy from *most realistic* (lowest value) to *least realistic* (highest value). The first position indicated the highest perceived accuracy with the situation described. The sampling rate of 4000 Hz ranked highest ($M_{rank} = 2.72$, $SD_{rank} = 1.42$), followed by 3000 Hz ($M_{rank} = 2.81$, $SD_{rank} = 1.40$), 2000 Hz ($M_{rank} = 3.09$, $SD_{rank} = 1.64$), 1000 Hz ($M_{rank} = 3.45$, $SD_{rank} = 1.86$), 5000 Hz ($M_{rank} = 4.00$, $SD_{rank} = 1.61$), and 6000 Hz ($M_{rank} = 4.91$, $SD_{rank} = 1.64$). We therefore chose the 4000 Hz sampling rate for our study, which was also described to resemble passing trees in open comments on first impressions.

For unimodal-vis and bimodal-vis+aud, we tested each of the two variations of the factor stimulus dynamics (static and oncoming stimuli) 15 times for each of the five speed variations. Thus, for each of the two conditions, each participant encountered 150 trials, divided into 5 blocks à 30 trials. In addition, we tested the unimodal-aud part serving as a manipulation check in two experimental blocks à 30 trials. After each block of 30 trials the participants could take a short break. The variation of stimulus dynamics was randomized across trials.

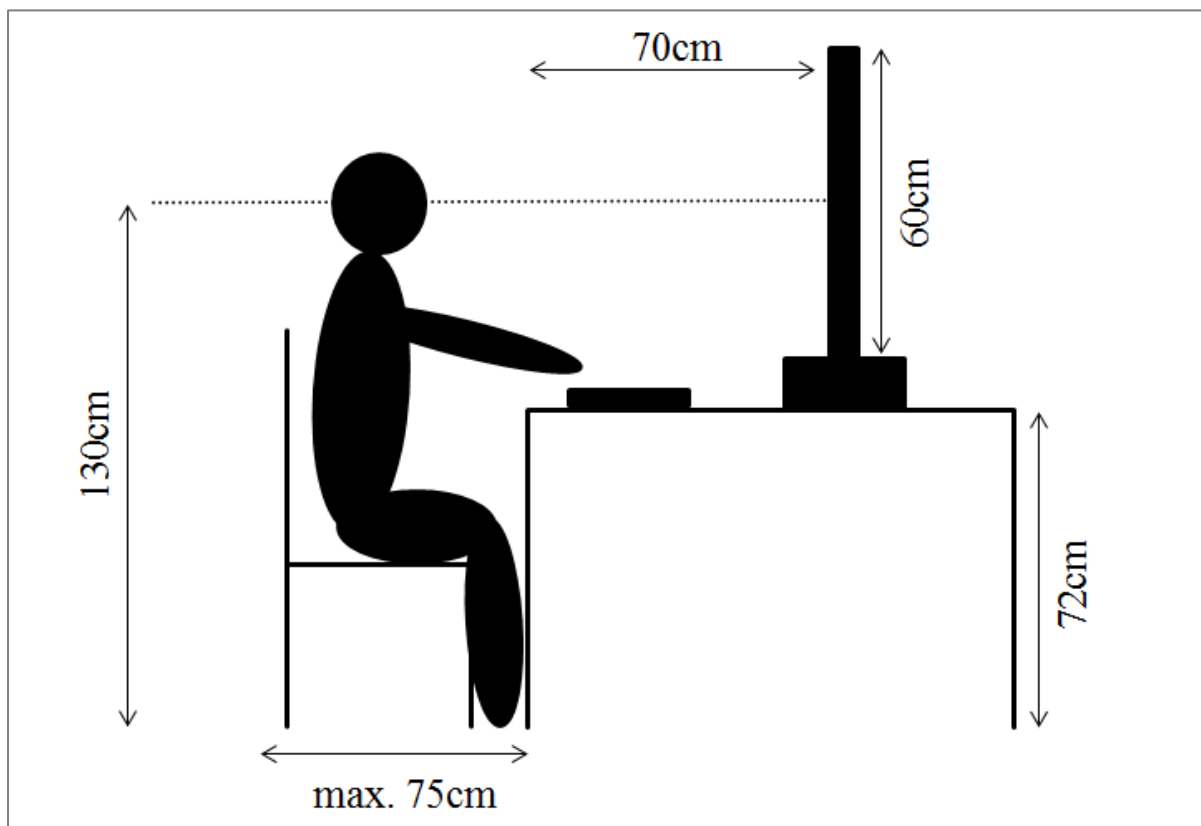
We conducted the experiment in a test room at the Institute for Automotive Engineering of RWTH Aachen University in Germany. We curtained off windows, ensuring comparable light conditions. Participants sat on a height-adjustable chair in front of a desk with a screen (Samsung 49" Flat QLED 4k with 60 Hz frame rate) and standard keyboard. They adjusted the height of the seat so that their eye level was at the level of the screen's center

(Figure 3) and sat centrally. The distance between the back of the chair and the desk was below 75 cm for standardized viewing angle and distance. Fleece patches were glued on the relevant keys Y (= the first video sequence was perceived faster) and M (= the second video sequence was perceived faster), ensuring that participants were able to detect them easily.

Participants wore headphones (Sennheiser HD 650) with audio interface (Focusrite Scarlett Solo 3rd Generation). Volume was constant for all participants with the computer's volume put at maximum and the audio interface at 50%.

Figure 3

Set-up and dimensions of experimental set-up in line with Köhler et al. (2023).



Note. Illustration of the participant sitting on a height-adjustable chair in front of a table holding the keypad and the screen. Heights and distances are illustrated.

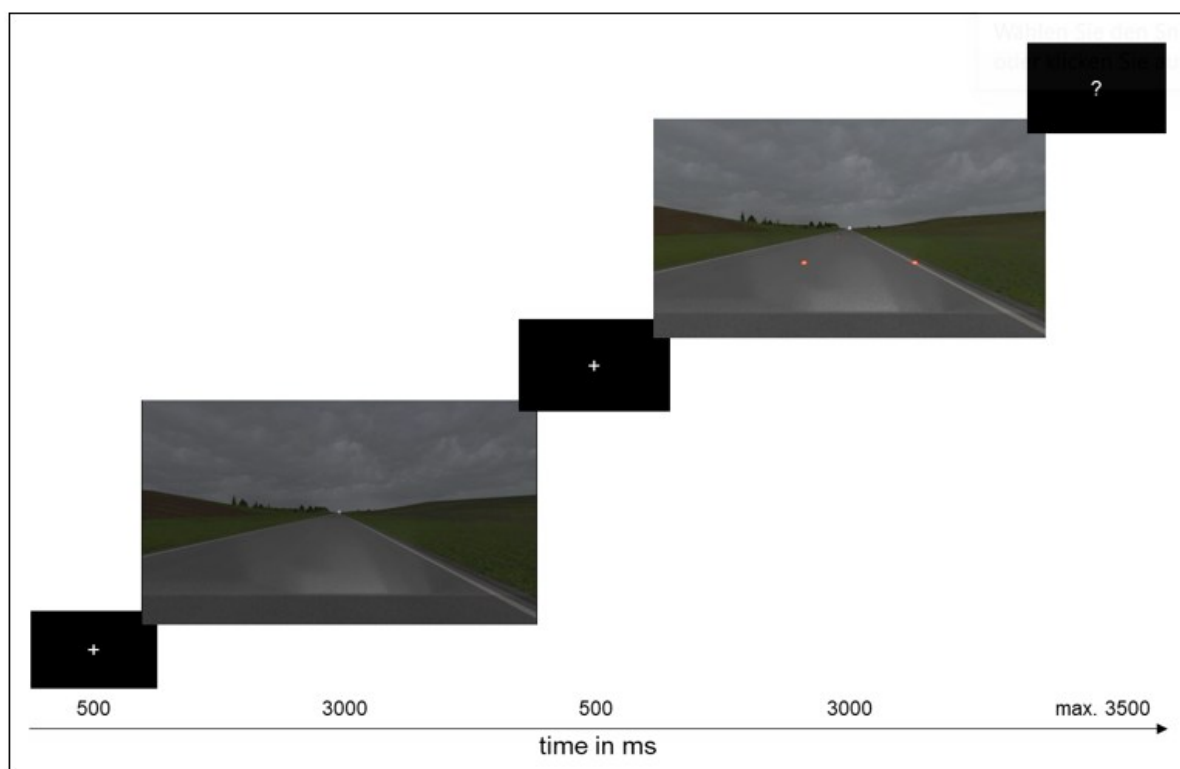
2.1.2 Procedure

We conducted Experiment 1A in July 2021⁴. Participants were welcomed, signed formal documents including giving informed consent to the study, and completed a pre-questionnaire. Sitting position and -height were adjusted according to Figure 3. We informed participants about the task via the screen for standardization. Participants would see two consecutively presented video sequences in each trial. When a question mark appeared on the screen in sequences including visual information or a short tone sounded in sequences with only auditory information, they rated whether they perceived the traveling speed in the first or the second video as faster. We set the maximum reaction time to 3500 ms to collect participant's impulsive reactions. If participants did not respond, the next trial started automatically after the time limit. Figure 4 illustrates the trial sequence.

⁴ Testing took place during the COVID-19 pandemic. We complied with the local Covid19 regulations at the time of testing. Participants tested negative for Covid19 and were alone in the testing room. They were connected to the experimenter via a video-conferencing system and did thus not have to wear a mask.

Figure 4

Exemplary trial sequence for unimodal-vis trials. Auditory information was added to the stimulus material of unimodal-vis trials for the bimodal-vis+aud trials (not displayed).



Note. Illustrations of the trial sequence with 500 ms of a black screen displaying a fixation cross, followed by either the video sequence (reference sequence or test sequence, depending on the randomization) with (bimodal-vis+aud) or without (unimodal-vis) auditory information or only auditory information for unimodal-aud. This was followed by a 500 ms-long inter-stimulus interval, followed by another video or auditory sequence (reference sequence or test sequence, depending on the randomization), and a black screen with a question mark to indicate participants to respond.

Participants had to focus on the fixation cross in the center of the screen. Participants started with a familiarization block of ten trials. The experiment took 75 to 80 minutes.

2.1.3 Design

We based the study on a 2 x 2 within-subjects design with repeated measures on the within-subjects factor *stimulus dynamics* (2 levels; static and oncoming stimuli) and the within-subjects factor *presentation modality* (2 levels; unimodal-vis and bimodal-vis+aud). Unimodal-aud served only as manipulation check and was not part of the experimental design. The dependent variable was the PSE in kilometers per hour (km/h). Significance was tested at $\alpha = .05$.

2.1.4 Sample

We used G*Power to estimate sample size a priori and conservatively assumed a medium effect size of $f = 0.25$ (Cohen, 1988) based on Köhler et al. (2023), who reported medium to large effects in a similar setting. For our within-subjects design with the within-subjects factor *stimulus dynamics* (2 levels; static vs. oncoming stimuli) and the within-subjects factor *presentation modality* (2 levels; unimodal-vis vs. bimodal-vis+aud) with a correlation among repeated measures of .50, we calculated that a sample size of 30 participants for each experiment would allow us to detect an effect of this size at $\alpha = .05$ with a power of .90 (Faul et al., 2007).

We recruited 36 participants for Experiment 1A. Ten data sets needed to be excluded for reasons outlined in the data analysis section, thus 26 participants remained for further analysis ($n = 12$ male, $n = 14$ female). This sample size would allow us to detect a medium effect size of $f = 0.25$ (Cohen, 1988) at $\alpha = .05$ with a power of .85 (Faul et al., 2007). The mean age of the remaining sample was 28.31 years ($SD = 12.21$ years, ranging from 18 to 61 years). 92.3 % ($n = 24$) were right-handed. All had normal or corrected-to-normal vision. Twenty-five participants held a driver's license for a mean duration of 10.80 years ($SD = 12.40$ years), ranging from 1 to 43 years. Kilometers driven within a year ranged from 10 to 20,000 km ($M = 5,648.40$ km, $SD = 5,833.70$ km).

2.2 Results

2.2.1 Data Preparation

Binary logistic regressions were calculated to determine the PSE for each experimental condition for every participant. We thus calculated six binary logistic regressions per participant, four for the unimodal-vis and bimodal-vis+aud presentation modalities needed to test our hypotheses and two for the unimodal-aud manipulation check. We used IBM SPSS Statistics 26.0 and 29.0 for all calculations.

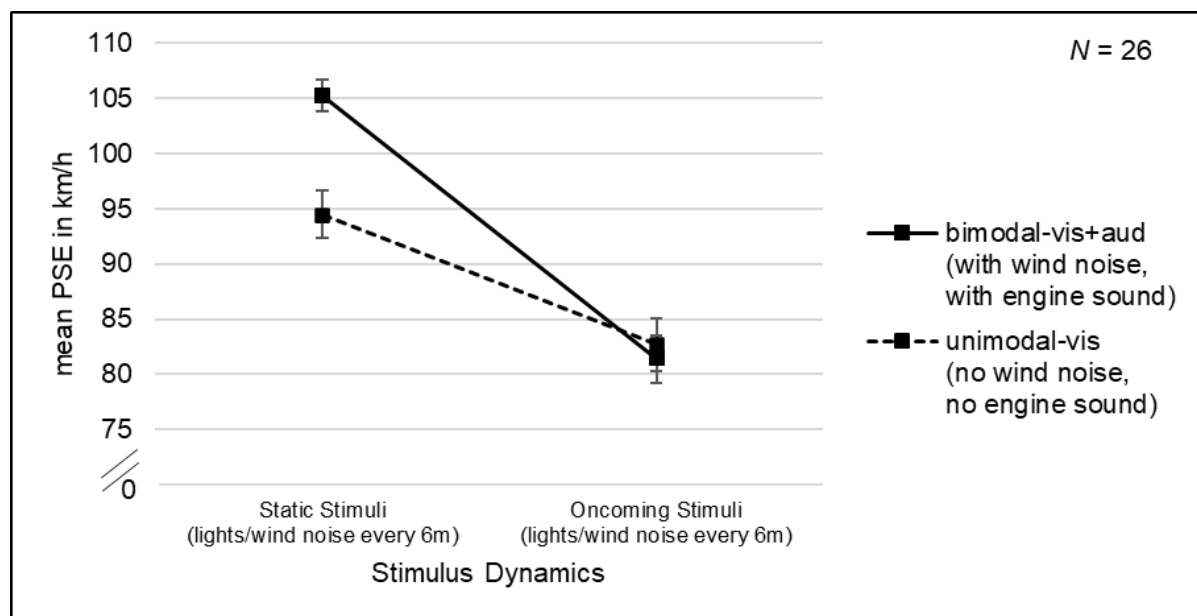
For calculating the PSE, the binary logistic regression must yield a significant result to assume a significant prediction between the predictor variable speed and the key response as outcome variable. Therefore, ten data sets with each at least one non-significant result in one of the four binary logistic regressions needed to be excluded for Experiment 1A, thus 26 subjects remained for further analysis.

2.2.2 Data Analysis

Figure 5 shows the PSE as a function of presentation modality and stimulus dynamics. Note that speed is perceived as faster when the PSE is lower.

Figure 5

Mean PSEs (in km/h) for static stimuli and oncoming stimuli in the unimodal-vis and the bimodal-vis+aud presentation modalities for Experiment 1A.



Note: Error bars indicate standard errors.

The 2 x 2 ANOVA with repeated measures on the within-subjects factor presentation modality (2 levels; unimodal-vis and bimodal-vis+aud) and the within-subjects factor stimulus dynamics (2 levels; static and oncoming) revealed a significant main effect for stimulus dynamics, $F(1,25) = 66.84, p < .001, \eta_p^2 = .73$, showing that the PSE was generally lower for oncoming stimuli than for static stimuli (oncoming stimuli: $M = 82.10, SD = 9.36$ vs. static stimuli: $M = 99.82, SD = 8.37$). We also found a significant main effect for presentation modality, $F(1,25) = 7.27, p = .012, \eta_p^2 = .23$, showing that the PSE was generally lower for unimodal-vis stimuli than for bimodal-vis+aud stimuli (unimodal-vis: $M = 88.57, SD = 9.79$ vs. bimodal-vis+aud: $M = 93.35, SD = 6.46$). The main effect for presentation modality, however, was qualified by a significant interaction between presentation modality and stimulus dynamics, $F(1,25) = 22.13, p < .001, \eta_p^2 = .47$, showing that the PSE for unimodal-vis stimuli was lower only with static stimuli but not with oncoming stimuli.

Specifically, the interaction showed that the reduction of perceived speed based on the oncoming stimuli was significantly larger for the bimodal-vis+aud presentation modality than for unimodal-vis (i.e., mean PSE reduction of 23.74 km/h, $t(25) = -9.73$, $p < .001$, $d_z = 1.91$, 95% CI [77.28, 85.68] for bimodal-vis+aud stimuli when tested separately vs. 11.70 km/h, $t(25) = -4.51$, $p < .001$, $d_z = 0.88$, 95% CI [77.82, 87.61], for unimodal-vis when tested separately). Note that with static stimuli, the unimodal-vis presentation modality led to a lower PSE than bimodal-vis+aud ($t(25) = -5.82$, $p < .001$, $d_z = 1.14$, 95% CI [89.77, 99.07]), but the larger reduction of the PSE with oncoming stimuli in the bimodal-vis+aud presentation modality even numerically (but not significantly, $t(25) = 0.50$, $p = .311$, 95% CI [77.28, 85.68]) decreased the PSE below that for the unimodal-vis presentation modality.

In the unimodal-aud manipulation check for Experiment 1A, only eight participants showed a significant logistic regression needed to calculate a PSE. A Wilcoxon signed-rank test showed a significant difference between static stimuli ($Mdn = 115.64$) and oncoming stimuli ($Mdn = 71.84$), $T = 36$, $z = -2.52$, $p = .012$, $r = .891$. This is in line with our assumption that auditory stimuli alone would affect speed perception, which would then be consistent with an added effect in bimodal stimulation relative to unimodal stimulation. Note, however, that this result needs to be interpreted with caution due to the low number of participants in this analysis.

2.3 Discussion

We conducted Experiment 1A in a laboratory setting to investigate the effect of visuospatial and acoustic stimuli on speed perception in a simulated driving setting. Participants encountered a simulated straight road with either static or oncoming stimuli. These were presented either unimodally (visuo-spatial stimuli in the form of lights on both sides of the road, unimodal-vis) or bimodally (visuo-spatial stimuli in the form of lights on both sides of the road enhanced with wind noise every time a light was passed, bimodal-vis+aud). The bimodal-vis+aud presentation modality was enhanced by a car's engine sound, while the unimodal-vis presentation modality did not contain any auditory stimuli.

We found that conditions with oncoming stimuli were generally perceived as faster (indicated by the lower PSE) than conditions with static stimuli. This is in line with the findings of Köhler et al. (2023) and suggests that it is likely that the optic flow (Palmisano, 2002; Gibson, 1950) or, in the case of bimodal stimulus presentation, a combined optic and acoustic flow (Pretto & Chatziastros, 2006) influenced participant's speed perception.

When comparing our results with that of Köhler et al. (2023), who only used unimodal visual stimuli without any added noise stimuli, we found that speed was perceived as significantly faster (indicated by the lower PSE) for oncoming stimuli than for static stimuli in both presentation modalities, unimodal-vis and bimodal-vis+aud. Furthermore, the unimodal-vis presentation modality, which had the same specifications as the same condition in Experiment 1B of Köhler et al. (2023) led to almost the same PSE values, thus exactly replicating the finding of this previous study. Remarkably, the effect of oncoming stimuli on perceived speed was much larger with bimodal-vis+aud stimuli, thus extending our previous findings. Notably, while the bimodal-vis+aud presentation modality was associated with higher estimated PSE when stimuli were static, this modality-specific influence was diminished with oncoming stimuli and was numerically even slightly reversed (i.e., lower for bimodal stimuli than for unimodal stimuli).

However, while the unimodal-vis presentation modality did not contain any auditory stimuli, the bimodal-vis+aud presentation modality contained not only auditory stimuli in the form of wind noise but also additional engine sound. This could have affected our results, so that we cannot specify with certainty whether the stronger effect of oncoming stimuli in the bimodal-vis+aud presentation modality relative to the unimodal-vis presentation modality might have been found due to the added wind noise on the bimodal-vis+aud presentation modality or due to the engine sound. We therefore conducted Experiment 1B and added engine sound to the unimodal-vis presentation modality to control for a potential confounding effect of the engine sound.

The increased effect of oncoming stimuli on speed perception when using bimodal-vis+aud stimuli is in line with the result of our unimodal-aud manipulation check. This manipulation check showed that traveling speed was perceived faster (indicated by a lower PSE) for oncoming auditory stimuli than for static auditory stimuli, even though the small number of significant logistic regressions to calculate the PSE limits its interpretability.

3. Experiment 1B

In Experiment 1B, we added engine sound to the unimodal-vis presentation modality (visual stimuli in the form of light spots on both sides of the road), which had not contained engine sound in Experiment 1A. The bimodal-vis+aud presentation modality (visual stimuli in the form of light spots on both sides of the road and corresponding wind noise whenever passing a light) contained engine sound in both Experiment 1A and Experiment 1B.

3.1 Method

We based Experiment 1A on Experiment 1B. We refer to Experiment 1A to avoid redundancies and point out differences.

3.1.1 Apparatus, Task, and Stimuli

Experiment 1B was an almost exact replication of Experiment 1A. In Experiment 1B, however, we added the same engine sound as in the bimodal-vis+aud presentation modality to the unimodal-vis presentation modality to control for a potential confounding effect of the missing engine sound in the unimodal-vis presentation modality in Experiment 1A. Since one file with the engine sound from Experiment 1A showed technical damage when preparing the stimuli for Experiment 1B, we re-recorded engine sound for all traveling speeds for Experiment 1B. Again, we recorded the data binaurally, aurally compensated and calibrated (BHS II from Head Acoustics) while driving with Volkswagen Golf VII 1.5 TSI ACT BlueMotion with 96 kW and seven gear DSG. This is closely comparable with the vehicle used for the engine recordings in Experiment 1A. Driving conditions were the same as for Experiment 1B. We used the same engine sound recordings for all conditions in Experiment 1B. The acoustic stimuli resembling wind noise when passing a light remained the same as in Experiment 1A.

3.1.2 Procedure

We conducted Experiment 1B in February and March 2022. The procedure was the same as for Experiment 1A.

3.1.3 Design

As in Experiment 1A, we based the study on a 2 x 2 within-subjects design with repeated measures on the within-subjects factor *stimulus dynamics* (2 levels; static and oncoming stimuli) and the within-subjects factor *presentation modality* (2 levels; unimodal-vis and bimodal-vis+aud). Unimodal-aud served only as manipulation check and was not part of the experimental design. The dependent variable was the PSE in kilometers per hour (km/h). Significance was tested at $\alpha = .05$.

3.1.4 Sample

We applied the same power analysis as in Experiment 1A. We recruited 33 participants for Experiment 1B. Eight data sets had to be excluded for reasons outlined in the data analysis section, so that data of twenty-five participants remained for analysis ($n = 11$ male, $n = 14$ female). This sample size would allow us to detect a medium effect size of $f = 0.25$

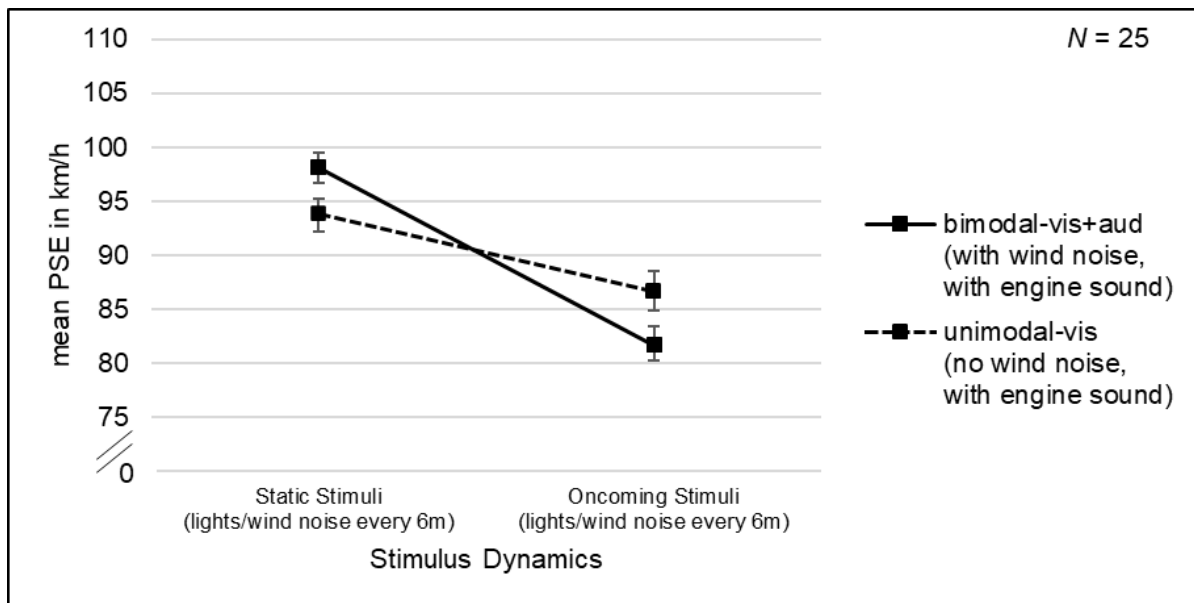
(Cohen, 1988) at $\alpha = .05$ with a power of .83 (Faul et al., 2007). Mean age of the remaining sample was 23.56 years ($SD = 5.36$ years, ranging from 18 to 42 years). 96 % ($n = 24$) were right-handed. All participants had normal or corrected-to-normal vision. Twenty-four participants held a driver's license for a mean duration of 6.67 years ($SD = 5.79$ years), ranging from 0 to 27 years. Kilometers driven within a year ranged from 0 to 20,000 km ($M = 4,574.00$ km, $SD = 6,198.98$ km). Participants in both experiments were naïve to the purpose of the study, did not receive monetary compensation, and participated voluntarily after giving informed consent. Participants in Experiment 1B had not participated in Experiment 1A before.

3.2 Results

As in Experiment 1A, binary logistic regressions were calculated to determine the PSE for each experimental condition for every participant. We used IBM SPSS Statistics 29.0 for all calculations. Again, for calculating the PSE, the binary logistic regression must yield a significant result to assume a significant prediction between the predictor variable speed and the key response as outcome variable. For Experiment 1B eight data sets, with each one non-significant result in one of the four calculated binary logistic regressions had to be excluded and data of twenty-five subjects remained for further analysis. Figure 6 shows the PSE as a function of presentation modality and stimulus dynamics. Note that speed is perceived as faster when the PSE is lower.

Figure 6

Mean PSEs (in km/h) for static stimuli and oncoming stimuli in the unimodal-vis and the bimodal-vis+aud presentation modalities for Experiment 1B.



Note: Error bars indicate standard errors. Bimodal-vis+aud was a replication of the same presentation modality in Experiment 1A.

The 2 x 2 ANOVA with repeated measures on the within-subjects factor presentation modality (2 levels; unimodal-vis and bimodal-vis+aud) and the within-subjects factor stimulus dynamics (2 levels; static and oncoming) revealed a significant main effect for stimulus dynamics, $F(1,25) = 62.33$, $p < .001$, $\eta_p^2 = .72$, showing that the PSE was generally lower for oncoming stimuli than for static stimuli (oncoming stimuli: $M = 84.16$, $SD = 8.26$ vs. static stimuli: $M = 95.98$, $SD = 6.62$). The main effect for presentation modality was not significant, $F(1,25) = 0.25$, $p = .623$, $\eta_p^2 = .01$.

Furthermore, like in Experiment 1A, we found a significant interaction between presentation modality and stimulus dynamics, $F(1,25) = 33.21$, $p < .001$, $\eta_p^2 = .58$. This interaction showed that the reduction of perceived speed based on the oncoming stimuli was significantly larger for bimodal-vis+aud than for unimodal-vis (i.e., a mean PSE reduction of 16.42 km/h, $t(24) = -4.70$, $p < .001$, $d_z = 0.94$, 95% CI [82.88, 90.44] for bimodal-vis+aud when tested separately vs. 7.21 km/h $t(24) = -8.91$, $p < .001$, $d_z = 1.78$, 95% CI [78.18, 85.14], for unimodal-vis when tested separately. Furthermore for static stimuli, the unimodal-vis condition led to a lower PSE than for the bimodal-vis+aud condition ($t(24) = -4.08$, $p < .001$, $d_z = 0.82$, 95% CI [91.01, 96.74]), but for oncoming stimuli this pattern was reversed, with the PSE being significantly lower for the bimodal-vis+aud condition than for the

unimodal-vis condition ($t(24) = 4.11, p < .001, d_z = 0.82, 95\% \text{ CI } [78.18, 85.14]$) (note that the same reversal occurred in Experiment 1A, but not to the degree that the PSE was significantly lower in the bimodal-vis+aud condition than in the unimodal-vis condition with oncoming stimuli).

In the unimodal-aud manipulation check for Experiment 1B, 14 participants showed a significant logistic regression as prerequisite to calculate a PSE. A Wilcoxon signed-rank test showed a significant difference between static stimuli ($Mdn = 103.33$) and oncoming stimuli ($Mdn = 82.64$), $T = 105, z = -3.30, p < .001, r = .881$, again supporting our assumption that auditory stimuli alone would affect speed perception.

To evaluate the influence (if any) of the added engine sound in the unimodal-vis presentation modality, we tested potential differences between the two unimodal-vis presentation modalities (without engine sound in Experiment 1A and with engine sound in Experiment 1B) post-hoc. A 2×2 mixed ANOVA with repeated measures on the within-subjects factor stimulus dynamics (2 levels; static and oncoming) and the between-subjects factor engine sound (2 levels; unimodal-vis with and without engine sound) revealed a significant main effect for stimulus dynamics, $F(1,49) = 38.63, p < .001, \eta_p^2 = .44$, again showing that the PSE was generally lower for oncoming stimuli than for static stimuli (oncoming stimuli: $M = 84.65, SD = 10.84$ vs. static stimuli: $M = 94.15, SD = 9.45$). The main effect for engine sound was not significant, $F(1,49) = 0.50, p = .484, \eta_p^2 = .01$, showing no difference between the two unimodal-vis presentation modalities (Experiment 1A without engine sound and Experiment 1B with engine sound). The interaction between stimulus dynamics and engine sound was also not significant, $F(1,49) = 2.18, p = .147, \eta_p^2 = .04$.

3.3 Discussion

In Experiment 1B, participants encountered the same experimental set-up and stimuli as in Experiment 1A, except for added engine sound to the unimodal-vis presentation modality. As in Experiment 1A, conditions with oncoming stimuli were perceived as faster (indicated by the lower PSE) than conditions with static stimuli.

Importantly, the bimodal-vis+aud stimulus presentation with both lights and overlaid wind noise showed a more than twice as large speed reduction from static to oncoming stimuli compared to the unimodal-vis (+engine noise) presentation modality. This is in line with our hypothesis that auditory information could intensify the visual information (e.g., Gagliano, 2016; Keshavarz et al., 2014) but only for oncoming stimuli. Oncoming stimuli therefore likely influenced a combined optic and acoustic flow (Pretto & Chatziastros, 2006) and lead to a

higher perceived speed (indicated by the lower PSE). This is in line with our expectation of a greater influence of oncoming stimuli and especially bimodal-vis+aud stimuli on speed perception.

4 General Discussion

We conducted two experiments in a laboratory setting to investigate the effect of visuospatial and acoustic stimuli on speed perception in a simulated driving setting. Our participants encountered a simulated straight road with either static or oncoming stimuli. These were presented either unimodally (visuospatial stimuli in the form of lights on both sides of the road, unimodal-vis) or bimodally (visuospatial stimuli in the form of lights on both sides of the road enhanced with wind noise every time a light was passed, bimodal-vis+aud). Unimodal-vis did not contain any engine sound in Experiment 1A but added engine sound in Experiment 1B. Participants indicated which traveling speed in two consecutive video sequences they perceived as faster. We therefore applied the method of constant stimuli (see Pretto et al., 2012). This led to the calculation of the PSE. The lower the PSE, the higher the perceived traveling speed.

In both experiments, we found that participants perceived conditions with oncoming stimuli as faster (indicated by the lower PSE) than conditions with static stimuli, most likely due the combined acoustic and optic flow (Pretto & Chatziastros, 2006). This is in line with Köhler et al. (2023), where results revealed that video sequences with oncoming lights were perceived as faster than those with static lights, but the present study showed that this effect is much stronger with bimodal stimuli including corresponding wind noise. This suggests that previous studies in fact underestimated the influence of oncoming stimuli on speed perception. We found this effect in both experiments with two different participant groups, Experiment 1A and Experiment 1B, indicating the robustness of this finding. This is also in line with the temporal ventriloquism hypothesis, suggesting that auditory information has likely reinforced the visual information when both modalities corresponded (Gagliano, 2016; Keshavarz et al., 2014; Ramkhalawansingh et al., 2016).

Furthermore, results revealed a significant difference between unimodal-vis and bimodal-vis+aud stimuli when encountering oncoming stimuli for Experiment 1B, but not for Experiment 1A, though the absolute values for bimodal-vis+aud oncoming stimuli remained the same. In Experiment 1A, conditions with unimodal-vis stimuli were generally perceived as faster (indicated by the lower PSE) than conditions with bimodal-vis+aud stimuli. We did not find this significant difference in Experiment 1B. Since the difference between

Experiment 1A and Experiment 1B was the added engine sound to the unimodal-vis presentation modality, the missing engine sound in the unimodal-vis presentation modality of Experiment 1A might have led to this difference. We therefore tested whether the presence of engine sound in the unimodal-vis presentation modality influenced our results. We did not find an influence of engine sound in the unimodal-vis presentation modality in the post-hoc analysis, suggesting that the missing engine sound in Experiment 1A should not have influenced our results very much. However, the influence of oncoming stimuli was generally lower in Experiment 1B than in Experiment 1A, also in the identical bimodal-vis+aud presentation modalities of both experiments. Given that these were separate samples of participants, it is possible that this small difference across experiments could also be attributable to a random sampling effect.

We tested a unimodal-aud presentation modality in the manipulation checks of both experiments. This, however, has limited external validity, since drivers would not drive by hearing alone. However, traveling speed was perceived as faster (indicated by a lower PSE) for oncoming auditory stimuli than for static auditory stimuli in both Experiment 1A and Experiment 1B. This strengthens the argument for the influence of auditory stimuli in speed perception. So even when visual information as the main source for estimating speed was not available (see, e.g., Köhler et al. (2023) for an overview), auditory stimuli could influence our participant's perception of traveling speed. Future studies could determine if this effect persists when adding a visual baseline to the auditory stimuli, with only the road but no visual experimental stimuli on the sides of the road visible. It would be worthwhile to investigate speed perception when visual and auditory information do not correspond to determine the potential influence of such stimulus combinations and understand underlying mechanisms in sensory integration even better. A study by Kwon et al. (2009) showed that visual information influenced speed perception more than auditory information when both input modalities did not correspond. Our results suggest that auditory stimuli alone influenced speed perception (see also Horswill and Plooy, 2008). Future studies could investigate the role of unimodal auditory stimuli further and should determine the role of auditory information that does not correspond to visual information, since auditory information likely affects visual perception in temporal discrimination tasks when the two sources of information are in conflict (Manabe & Riquimaroux, 2000; Morein-Zamir et al., 2003; Shams et al., 2002, 2004).

Note that the post-hoc comparison on the influence of engine noise might point to a potential limitation of our study. Firstly, the concurrent engine sound of Experiment 1A and Experiment 1B was slightly different since it was re-recorded for Experiment 1B. We

performed Experiment 1B a considerable time after Experiment 1A, which led to the re-recording. While we regard the two vehicles used for recording engine sound as comparable, we cannot rule out a potential effect of this on our results. Future studies should ensure using the same audio files to rule out potential confounding effects. Secondly, there might be differences in the samples of Experiment 1A and Experiment 1B. While we aimed at comparable samples in terms of gender distribution and mean age, we cannot rule out that sample differences lead to our results especially regarding the influence of concurrent engine sound. We also had to exclude ten data sets per experiment from the data analysis because they each had at least one non-significant result in one of the four binary logistic regressions needed for a complete comparison in our analysis. While these were distributed rather evenly across the counterbalanced order of presentation modalities, this could have influenced the comparability of the experimental conditions and the samples of both experiments.

Furthermore, we presented different speed levels for oncoming stimuli (ranging from 60 km/h to 100 km/h) than for static stimuli (ranging from 80 km/h to 120 km/h), which might have led to limited comparability of oncoming and static stimuli. However, in line with Köhler et al. (2023), we think that this is unlikely for the following reason: We assumed that the PSE within one level of the factor stimulus dynamics (static lights vs. oncoming lights) is always located in the same spot, since the PSE indicates where a condition was perceived as equal to a reference sequence, in our case a driving sequence without light or wind stimuli. Even if we had tested the same speed levels for incoming and static stimuli, the PSE would have likely been in the same spot as we found it. We also aimed at having the presented traveling speeds scattered around the actual PSE, which we expected to be lower for oncoming stimuli, hence the lower traveling speeds for the video sequences for this condition.

Transferring our findings regarding the presumably limited influence of engine sound to a more applied setting in real traffic, the condition with concurrent engine sound is the more ecologically valid setting and reflects real driving conditions more accurately. Sound isolation of vehicles has increased over time and higher soundproofing can usually first be found in newer vehicles (e.g., Bijsterfeld, 2010). A lower engine sound for vehicle occupants is also true for most electric vehicles (e.g., Govindswamy & Eisele, 2011). Our results do not suggest that a roadside intervention based on the stimuli tested in our study might lead to increased effectiveness when slowing down speeding drivers when they hear engine sound, but this requires further investigation.

The results presented in this paper provided further insights into the influence of sensory information, especially bimodal information, on speed perception. This has the potential

to aid the development of countermeasures against speeding that go beyond mere punishment by fining speeding drivers but can aid drivers that might be unaware of a potentially unsafe too-high speed in adjusting driving speed to a safer level. Further development of applied measures to reduce speed as described by Köhler et al. (2022) should consider not only visual information but also auditory information, such as allowing or heightening sounds from outside the vehicle. Whilst visual oncoming stimuli may be realized in the form of infrastructure countermeasures, as outlined by Köhler et al. (2023), the potential of corresponding auditory stimuli could be surveyed as in-vehicle countermeasure. A possible setting for subsequent studies could be a driving simulator allowing the use of real vehicles and the presentation of critical scenarios to learn more about the influence of bimodal stimuli on potential speed reduction while driving. While the present study was conducted under laboratory conditions, further research should determine the applicability in more naturalistic traffic settings.

4.1 Conclusion

Taken together, our study extended previous findings on the role of optical flow in speed perception in important ways. We confirmed the influence of unimodal oncoming visual stimuli on speed perception, as in previous studies, but we demonstrated that the addition of auditory stimuli substantially increased this influence on speed perception. Bimodal oncoming stimuli should therefore be strongly considered in the development of countermeasures against speeding in traffic. Future research should also aim at transferring our findings to a more naturalistic setting and investigate the effect of non-corresponding auditory information on speed perception to understand underlying mechanisms even better.

Declarations

Ethics approval and consent to participate

We based the specifications of the studies reported in this paper on the declaration of Helsinki and the guidelines of the Institute for Automotive Engineering of RWTH Aachen University. Based on these and since we did not conduct any clinical trials, there was no need for ethical approval. The studies were performed on a standard desk with a screen, keyboard, and headphones and no other risks than required for a regular office job. Regardless, participants gave their fully informed consent before participating in the study. This included information on and consent to data protection guidelines (according to GDPR of the European Union) and the right to stop their participation anytime without having to give a reason for this and without fearing any consequences. Information on the experiment's hypotheses, which could not be given before participation for methodological reasons, was given to participants in a debriefing after participation.

CRedit authorship contribution statement

Anna-Lena Köhler: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iring Koch:** Writing – review & editing, Validation, Supervision. **Stefan Ladwig:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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