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ORIGINAL ARTICLE

Driving emotions: using virtual reality to explore the effect of low and high arousal on driver's attention

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Abstract
The role played by emotions and attention is crucial for the development of advanced driver assistance systems that improve safety by flexibly adapting to the current state of the driver. In the present study, we used immersive virtual reality as a testing tool to investigate how different emotional states affect drivers' attention in a divided attention task. Two different emotional states, diversified by valence and arousal, were induced before performing a divided attention task in a driving simulation. The experimental task developed for this study allowed us to explore if and how two different emotional states can affect the way drivers divide their attention between a central driving-related task and a peripheral visual task. Our results showed that scared drivers presented lower reaction times at the central task compared to relaxed drivers. On the contrary, the emotional state did not affect the performance at the peripheral task, which revealed instead a significant effect of the eccentricity at which the visual stimuli were presented, influencing both the accuracy of targets' perception and participants' reaction times.

Keywords Virtual reality · Attention · Emotions · ADAS

1 Introduction

According to the latest annual report by the European Road Safety Observatory (European Road Safety Observatory 2021), EU still has an average of 44 road deaths per million inhabitants. Statistics for other regions of the world are similar or worse. Even though a precise figure is hard to obtain, it is believed that a significant fraction of road accidents are caused by human error. Distraction is often the cause behind a road accident (Stewart 2022), but the emotional state of the driver is a factor that should not be underestimated because it is able to directly influence driving behaviors, and affects drivers' attention and perception. For this reason, the automotive industry is rapidly moving toward the development and introduction of monitoring systems able to recognize drivers' emotional states (see Zepf et al. (2020) for a survey on the topic). In the literature, most of the research works that explore the interaction between emotions and driving behavior focuses on traffic-related attributes, such as driving speed, infractions, distance from other vehicles, aggressive behaviors, or accidents (Deffenbacher et al. 2002, 2003; Jeon and Walker 2011). For instance, in a study involving taxi drivers and performed in real-life driving situations, five different emotional states, two positive (i.e., happy and relaxed), two negative (sad and angry), and a neutral state, were considered while monitoring driving speed. Results showed that negative emotions significantly increase driving speed, while a neutral emotional state was related to a decreased speed. Interestingly, relaxed and happy emotional states did not affect driving speed (Kadoya et al. 2021). Emotions also affect hazard perception. In a recent study, positive and negative emotional states have been explored in relationship with hazard perception in young and old drivers using simulated driving environments. The results show how young drivers reported the highest perceived hazard for negative emotions, as opposed to older drivers who

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reported the highest perceived hazard while experiencing positive emotions (Huo et al. 2022). Drivers' emotional state also affects the sustainability of their vehicles, as emotions heavily impact electric cars' battery range (Dominguez et al. 2022; Lamanuzzi et al. 2020).

All the studies reported above have focused on exploring the interaction between different emotions and driving behavior. However, recognizing an emotion and collecting measurements on it in a real-life scenario is not a trivial task. For this reason, one of the most widely used experimental methods in studies on the topic consists of using driving simulations preceded or accompanied by a phase of induction of the desired emotional state. Over the years, several methods have been developed for emotion induction, each of them based on different mechanisms and usually defined as "Mood Induction Procedures (MIPs)" (Westermann et al. 1996; Jallais and Gilet 2010). Images, sounds, and videos are among the traditional media for emotion induction and include the mostly adopted databases in this sense. Previous works on the effect of emotions on driving behavior often relied on these means (e.g. Jones et al. (2014); Chan and Singhal (2015); Pêcher et al. (2009); Zhang et al. (2022), while others included different techniques, such as autobiographical recall (Jeon and Zhang 2013; Jeon 2016) or combinations of autobiographical imagination, and music Steinhauser et al. (2018); Huo et al. (2022).

Anger seems to be the most influencing and studied emotional state in the driving context, with a huge amount of data on the topic. Several scales and measures have been developed to assess angry drivers and their behavior (e.g., Deffenbacher et al. (1994); DePasquale et al. (2001); Stephens et al. (2019)). Studies based on naturalistic data have shown that compared to not aggressive drivers, aggressive drivers have 35 more chances of being involved in a crash (Dingus et al. 2016). They also seem to be more prone to risky behaviors affecting themselves and other road users (Precht et al. 2017; Abdu et al. 2012; Zhang et al. 2022). While research has mostly focused on anger, less empirical research has been performed on other affective states. For example, sad drivers showed either similar (Jeon 2016) or different driving-related behaviors when compared to angry drivers. Other works, used different factors from the appraisal theory and focused on the emotional outcomes that traffic situations have on the emotional state of drivers (Smith and Lazarus 1990; Scherer et al. 2001), highlighting the effect of anger and fear on risk perception (Lu et al. 2013). In road traffic safety, positive affects are often considered less able to induce vigilance and alertness in drivers (Lewis et al. 2007); whereas, negative emotions, like fear or tension, are more used (Lewis et al. 2008) than their positive counterparts. However, fear does not always seem to effectively reduce risky behavior. As reported in Cutello et al. (2021), risky driving behaviors in young drivers were heightened after seeing 2D and Virtual Reality (VR) fear-related content connected to road safety; while, positive messages correlated with a reduced proneness to risky behaviors.

A vast number of research works also considers the relationship between emotions and attention, focusing on the role that emotionally relevant stimuli may have in driving our attention. For example, fear-relevant visual stimuli can be detected significantly faster than neutral or fear-irrelevant stimuli (Öhman et al. 2001). It is also well known the special role played by human faces expressing emotions, especially because the information conveyed may be relevant for survival and adaptation. Expressions of anger or fear can be detected even before the face becomes the focus of attention, and that information can then be used by the visual system to determine the following attention allocation (Gerritsen et al. 2008). The relationship between emotion and cognition is also supported by neurological evidence, with different activation of brain areas during cognitive tasks that involved also emotion-related stimuli (Pessoa 2008) and different temporal thresholds for access to consciousness during masked visual perception tasks involving distinct affective states, with a lower threshold for negative moods (Kuhbandner et al. 2009). Focusing on negative emotions such as anger and fear, Finucane (2011) reported how the latter emotional state resulted in lower reaction times during a selective attention task, while (Soares et al. 2009) did not report differences between fear-related pictures and non-fear-relevant pictures in a visual search paradigm using animals pictures, highlighting, however, a slower disengagement of attention.

Still, these findings explored how the external emotional quality of the stimuli affects our attention. However, emotions can also affect the way individuals perceive and allocate their attention while experiencing a particular emotional state. On this point, fewer works considered the effect of emotions on drivers' attentive and perceptive attributes. For example, it has been reported that different emotional states also affect drivers' perception and attention allocation in different ways. In a localization task of road elements, sad and angry drivers showed respectively, higher error rates and slower performances compared to drivers with a neutral mood (Jallais et al. 2014). Steinhauser et al. (2018) explored the effects that emotional states of anger, calmness, and happiness have on driving domain, for example by promoting aggressive behaviors, or by influencing attentive processes. A recent work explored the effect of different emotional states on visual cognitive efficiency, analyzing drivers' fixation time and identification accuracy to different visual cognitive tasks. Their results showed that emotions significantly affect drivers' visual perception, with surprise, fear, anxiety, helplessness, and pleasure generally decreasing the performance at different visual cognitive tasks (Liu et al. 2022).

In the driving domain, most of the traffic-related information is acquired through the visual channel. An important concept regarding human visual perception and attention span is represented by the Functional or Useful Field of View (UFOV) (Sanders, 1970; Ball et al., 1988), defined as the total visual field area in which useful information can be acquired within one eye fixation (i.e., without eye or head movements). The UFOV size represents a good predictor of traffic crash risk (Ball et al. 1993; Clay et al. 2005) and its assessment, that evolved over the years (Owsley 2013), is now a widespread measure of driving readiness, especially for older individuals. The test is composed of three sub-tests. In the first, the observer is required to focus only on a central task and discriminate a visual target. In the second sub-test, the central task is accompanied by a simultaneous peripheral task in which the observer has to locate a peripheral target presented with an eccentricity of 10°, 20°, or 30° along any of eight possible radial directions. Finally, the third sub-test replicates the second one with the addition of peripheral distracting stimuli. The eccentricity of a visual stimulus significantly affects visual and attention processes (e.g., Edwards and Goolkasian (1974); Carrasco et al. (1995); Adam et al. (2008); Staugaard et al. (2016)). Similarly, task complexity and the relative priority given to multiple tasks can also influence peripheral perception (Rogé et al. 2002). Considering perception and eccentricity, Carrasco et al. (2003) found that the speed of information processing varies with eccentricity, with faster processing for same-size stimuli appearing at 9° than 4° eccentricity.

The goal of the present work is to explore the effects that different emotional states, characterized by low and high arousal, have on drivers' attention and on the way they perceive and react to central and peripheral stimuli. To do so, we developed a divided attention task in an immersive VR driving simulation. Participants were required to focus on a central visual task while simultaneously attending to peripheral stimuli, presented at different eccentricity values. Since the experimental task developed for the present work was implemented in immersive VR, we decided to use as MIP a combination of sounds and affective virtual environments specifically designed and developed for inducing distinct emotional responses in the user (Dozio et al. 2021, 2022). The choice of a setup entirely based on a head-mounted display (HMD) was made to provide an immersive and continuous experience, avoiding interruptions between the induction of the desired emotional state in the participants and the beginning of the experimental tasks. In addition, we further smoothed the transition between the two phases by keeping the sounds of the affective VR environments to extend the effect throughout the driving-related experimental tasks. On this point, HMD-based driving simulations proved to deliver a similar experience to desktop-based ones, with the main differences usually linked to presence and immersiveness, and perceived simulator sickness, but usually limited to long-running experiences (Cao et al. 2020; Malone and Brünken 2021).

The current paper proposes a fully immersive methodology to explore the interaction among emotional states, reaction times, and perception accuracy in driving contexts. Our results showed a difference in the reaction times for the central task depending on the emotional response induced, with faster responses for scared drivers. However, the emotional state did not significantly affects participants' performance in the peripheral task, where the most influencing factor was instead represented by the eccentricity of the visual stimulus, with significantly slower reaction times and lower detection accuracy for the most peripheral stimuli. The results obtained provide new insights concerning the dynamics that regulate attention and emotions, shedding light also on the multifaceted aspects that must be taken into account when utilizing VR as a testing tool in scenarios involving visual perception and visuospatial attention.

2 Materials and methods

In the following section, we present the procedure, the experimental task performed by the participants, the experimental setup, and finally the analysis performed on the data collected during the experiment.

2.1 Participants

The study involved a total of 30 participants (11 female) aged between 21 and 43 ($M = 28.77$; $SD = 4.17$) who voluntarily took part in the experiment. All had normal or corrected to normal vision. Possessing a driving license was a requirement for participating in the study. The majority of the participants had their driving license for more than 5 years (86.7%), and 13.3% for more than 1 year.

Each participant provided written informed consent before taking part in the study. All data were collected anonymously. The study was approved by the Politecnico di Milano Ethical Committee.

2.2 Procedure

Before starting the experiment, participants were asked to read and sign a consent form. Then, they were instructed about the structure of the study. After this, participants had to fill in a questionnaire in which they were asked to rate their experience with VR technology, the number of years since they obtained their driving license, and to evaluate their current emotional state through the 9-point scales of the Self-Assessment Manikin (SAM) (Bradley and Lang 1994), assessing valence, arousal, and dominance. Once

the questionnaire was completed, participants were asked to wear an HMD, and they were guided through a short training of the experimental task. When they felt confident with the procedure, they were allowed to proceed with the next step, which consisted in exploring the affective VR environment. The training phase lasted on average 3 min; while, the affective VR environments had a fixed duration of 90 s. As soon as this step was completed, the driving simulation was presented and participants were free to start the experimental task which lasted about 3 min. Once participants completed the experimental task, they were asked to remove the headset and complete the SAM questionnaire again. The choice of collecting valence and arousal rates at the end of the experimental task and not right after the exploration of the affective VR scenario was made to avoid interruptions between the MIP and the actual experimental task that could have resulted in a detachment from the ongoing experience, with a consequent reduction in the sense of presence and immersiveness, finally undermining the effectiveness of the MIP (Diemer et al. 2015), and also because the emotion induction procedure was maintained during the driving task using the same sound stimuli of the affective scenarios. The entire experiment lasted about 15 min. To avoid possible learning effects, the training phase was characterized by the same features of the experimental task, but was located on a different track and characterized by a different distribution of braking points and target appearances. During every phase of the study, the HMD view presented to the participants was replicated on the laptop monitor to which the HMD was connected. The experimenter monitored the execution of all the different steps that constituted the presented study. The study procedure is depicted in Fig. 1.

2.3 Emotion induction

Participants explored one of two affective VR environments developed and tested in Dozio et al. (2021, 2022) and adapted to immersive VR. One was designed to elicit fear and involved exploring a dark house, full of scary elements and characterized by ominous and eerie sounds. The other was meant to induce relaxation and was set on a tropical beach during sunset, with the sounds of waves, seagulls, and birds chirping in the background. Both scenarios had a fixed duration of 90 s. After exploring the affective VR environment, the sounds characterizing each scenario were maintained during the following experimental task to prolong participants' emotional response throughout the experiment.

2.4 Experimental task

In the VR scenario, participants were seated in the driving seat of a left-hand driving vehicle (ego) located on an urban road. A leading vehicle was initially located at a distance of 30 m. When participants were ready, both the ego and the leading vehicle started to accelerate at 5 m/s until a speed of 13 m/s was reached, then both proceeded on a pre-defined track maintaining a constant speed of 13 m/s and following a right-hand traffic flow. The experimental task consisted of a divided attention task, constituted by a central and a peripheral task. Concerning the central task, participants were asked to focus on the leading vehicle in

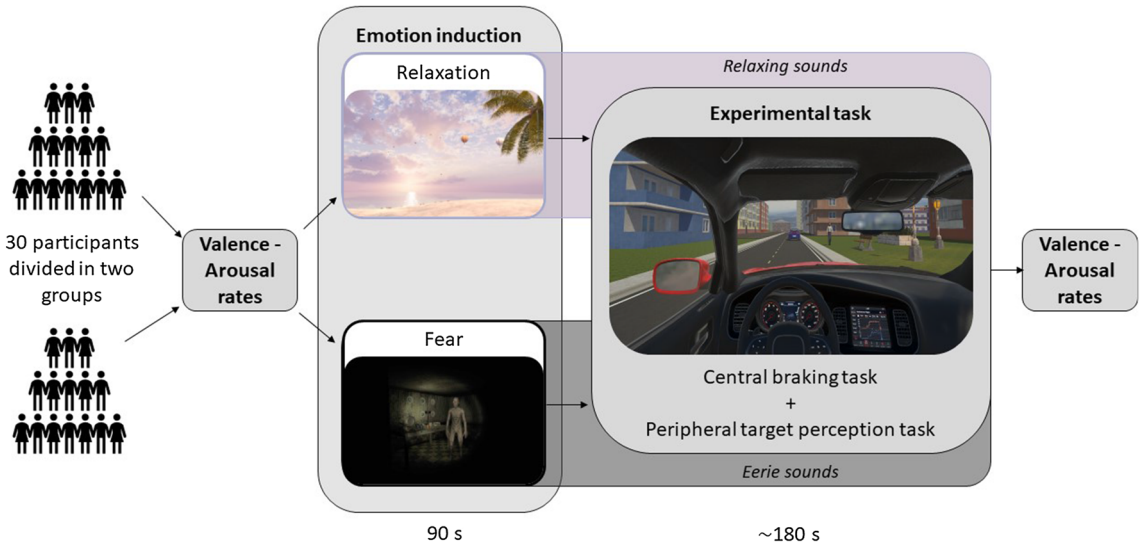


Fig. 1 Schematic representation of the experimental procedure. Participants were randomly divided in two groups and asked to rate their current emotional using the SAM valence and arousal dimensions. Then they were asked to explore one of the two affective VR environment and perform the experimental task. Finally, they were asked to rate again their emotional state

front of them for the entire duration of the experiment. During the ride, the leading vehicle performed 10 braking actions distributed along the track, reaching a complete stop in approximately 2 s in each brake and restarting after a time interval that ranged between 2.5 and 4 s, accelerating at 5 m/s until reaching the speed of 13 m/s.

Participants' central task was to perform a braking action on the ego vehicle in response to the braking of the lead vehicle. The braking action was achieved by pressing a trigger on the right controller. Both vehicles had the same characteristics in terms of speed, acceleration, and deceleration. As soon as the brake button/pedal was released, the ego vehicle would accelerate again at 5 m/s until the speed of 13 m/s was regained. In the event that the distance between the two vehicles was equal to or below 20 m due to delayed braking actions, the system automatically managed the restart of the ego vehicle to restore the original distance of 30 m.

At the same time, participants were required to perform a peripheral task, which consisted in press any left controller button any time a visual target (i.e., a pedestrian) appeared on the left or right side of the road. Targets could be located at an eccentricity of ±15°, ±20°, ±30°, appearing randomly on the right or left side of participants' vehicle, though this distinction was not considered during the analysis, where results regarding eccentricities of the same magnitude and opposite side were aggregated. Therefore, this variable could assume three levels: eccentricity = 15°, eccentricity = 20°, and eccentricity = 30°. A total of 15 targets appeared along the track, five for each eccentricity level. Since the distance between the ego and the leading vehicle could slightly change depending on the participants' reaction times at the central task, peripheral targets automatically adapt their lateral position to match the three eccentricity levels cited above. Figure 2 shows a view of the VR environment.

The eccentricity values used in the current study were chosen to explore differences in perception accuracy between the more peripheral measure used in the original UFOV procedure (i.e., 30°) (Ball et al. 1988), and values closer to the actual side of the road (i.e., 10° and 15°), representing a plausible dangerous situation for a driving context. The target appearance time was set at 125 ms and kept constant for all the eccentricity levels. This was made for two main reasons. Initial works on visual processing speed used a 125 ms presentation time (Sekuler and Ball 1986), which has been extended to cover a range from 16.67 to 500 ms in subsequent versions of the UFOV assessment (Edwards et al. 2006; Owsley 2013). Considering this, an appearance time of 125 ms represented a good compromise that allowed us to stay close to the lower threshold used in recent tests, but not too close to make the task excessively complex for participants of different ages and maybe not completely accustomed to VR technology. The second reason was due to practical needs. Since participants were virtually seated in a moving vehicle, longer target appearance times would have resulted in evident changes in eccentricity, which had to be avoided being eccentricity our independent variable. Finally, targets' distance from the participants' position was always 25 m, assuming the participants' position as zero and measuring in the direction of the ego vehicle movement. This distance was chosen to match the average distance of the leading vehicle during the experiment, as observed in a pilot study involving 9 participants conducted before the actual experimental phase. To ensure a correspondence between the real world and the VR environment, the scenario was built assuming that 1 Unity unit corresponds approximately to 1 m in the real world. To do so, all the elements

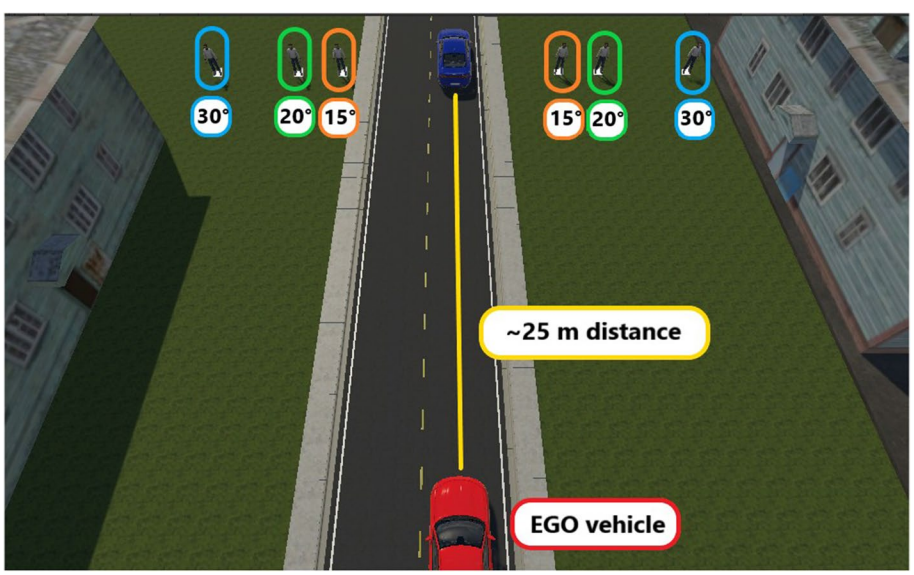


Fig. 2 Overview of the VR environment with targets' location

constituting the scenario were proportionate following this assumption (e.g., pedestrian height was approximately 1.8 units; lane width was approximately 4 units).

2.5 Study design

The experiment followed a mixed design. The emotional states induced in the participants constituted the between-subjects factor, and determined two experimental conditions. The participant sample was split into two groups, one for the relaxed condition, induced using the relax VR scenario, and one for the fear condition, induced through the fear VR scenario. The different eccentricities of targets' appearances represented the within-subjects factor. As described above, the targets' eccentricity represented the lateral position with respect to the center of the participants' field of view. The dependent variables were constituted by the performance at the central and peripheral task, measured in:

- Central task - Braking Reaction Time (RT_b): the time interval measured in ms from the moment in which the leading car started to brake and the moment in which participants pressed the breaking command. A brake reaction was considered valid only if it occurred within 2.5 s after the beginning of the leading car braking action.
- Peripheral task - Target Reaction Time (RT_t); the time interval measured in ms from the moment in which the visual target (i.e., a pedestrian) appeared and the moment in which participants confirmed to have seen it by pressing any right controller's button. To avoid random pressings, participants' responses were recorded only one time in an interval that lasted 2 s after each target appearance. After that interval, the target was counted as missed.
- Peripheral task - Target perception accuracy: the number of targets missed for each eccentricity level.

2.6 Experimental setup

The experimental task was performed in a VR scenario developed with Unity engine (version 2020.3.23). Participants were using a Meta Quest 2 headset (resolution 1832 × 1920 per eye; refresh rate 72 Hz) and Touch controllers. Throughout all the tasks, participants remained seated. During the training session, participants were asked to adjust the seat height in order to find their best position inside the VR vehicle. The experimental setup is depicted in Fig. 3.

Fig. 3 Experimental setup used in the current study

2.7 Data analysis

An a priori statistical power analysis to estimate sample size using G*Power was performed. We set a repeated measures ANOVA with the three conditions as a within-participants factor and the two emotional responses elicited as a between-participants factor. Approximately 30 participants are required to obtain a power of 0.95, an alpha level of 0.05, and a medium effect size ($f = 0.3$) (Faul et al. 2007).

We performed two normality tests (i.e., Kolmogorov–Smirnov and Shapiro–Wilk) on all the data collected during the experiment. Concerning the emotional response measured on the SAM valence and arousal scales, data did not follow a normal distribution and were analyzed applying a Wilcoxon signed-rank test to compare each participant's response before the emotion induction procedure and at the end of the experiment. Furthermore, we performed a Mann–Whitney U test on the measures collected at the end of the experiment, to check differences between the two conditions. Similarly, the data related to the central task (RT_b) were not normally distributed and we therefore decided to proceed with a nonparametric Mann–Whitney U test to compare data between the two experimental conditions. A post hoc power analysis was performed using G*Power, resulting in a statistical power of 0.86 with a sample size of 15 participants per group. Considering the peripheral task, RT_t data were normally distributed and were analyzed applying a one-way repeated measures ANOVA with eccentricity as a three levels within-factor, and the two experimental conditions as the between-subjects factor. On the contrary, data concerning the number target missed for each eccentricity level were not normally distributed. We therefore performed a nonparametric Mann–Whitney U test to check differences between the two experimental conditions, followed by a post hoc analysis with Wilcoxon signed-rank test to explore differences between the three eccentricity levels.

3 Results

In this section, we report the results of the analysis conducted for the experimental tasks. For the central task, we report the differences identified in participants' reaction times related to the emotional response induced before starting the task. For the peripheral task, we present how participants' reaction times and target perception vary according

to the eccentricity of the visual target and depending on the emotion induced. Descriptive statistics are reported in Table 1.

3.1 Emotion induction

The results of the Wilcoxon signed-rank test highlighted a statistically significant change in valence and arousal measures before and after the emotion induction procedure for both the fear ($Z_{\text{Valence}} = -3.336$; $p < 0.001$); ($Z_{\text{Arousal}} = -3.448$; $p < 0.001$) and the relax condition [($Z_{\text{Valence}} = -3.176$; $p = 0.001$); ($Z_{\text{Arousal}} = -3.461$; $p < 0.001$)]. Thus, we checked the results of the Mann–Whitney U test to compare the valence and arousal measures collected before and after the emotion induction procedure. As expected, the analysis of the valence and arousal rates collected before the emotion induction procedure did not identify significant differences ($p > 0.05$) between the two groups. On the other hand, the results concerning the rates collected at the end of the experiment showed that valence rates in the fear condition significantly differed from those obtained in the relax condition ($U_{\text{Valence}} = 9.5$; $Z = -4.362$; $p < 0.001$). The same significant difference was identified for the arousal measure ($U_{\text{Arousal}} = 0$; $Z = -4.817$; $p < 0.001$). More specifically, valence rates were significantly higher in the relax condition ($M = 6.87$; $SD = 0.91$) compared to the fear condition ($M = 4.20$; $SD = 1.37$). On the contrary, arousal rates were significantly higher in the fear condition ($M = 6.53$; $SD = 1.4$) compared to the relax one ($M = 2.27$; $SD = 0.46$).

3.2 Central task - RT_b

The analysis of the braking reaction times revealed a significant difference between the two conditions [$U(N_{\text{Fear}} = 150; N_{\text{Relax}} = 150) = 4770$; $Z = -8.626$; $p < 0.001$)]. Scared participants braked earlier ($M = 537$ ms; $SD = 116$ ms) in response to the leading car braking action compared to relaxed drivers ($M = 760$ ms; $SD = 284$ ms).

3.3 Peripheral task - RT_t

Results of the one-way ANOVA showed a significant effect of eccentricity [$F(1.684, 136.437) = 46.322$; $p < 0.001$; $\eta_p^2 = 0.364$]; while, the interaction between eccentricity and the conditions was not statistically significant [$F(1.684, 136.437) = 1.266$; $p > 0.05$; $\eta_p^2 = 0.015$]. Pairwise comparison between the three eccentricity levels showed that targets presented at 30° ($M_{\text{fear}} = 718$ ms; $SD_{\text{fear}} = 180$ ms; $M_{\text{relax}} = 732$ ms; $SD_{\text{relax}} = 200$ ms) of eccentricity correlated with slower RT, significantly different from those related to targets presented at 15° ($M_{\text{fear}} = 508$ ms; $SD_{\text{fear}} = 93{,}9$ ms; $M_{\text{relax}} = 595$ ms; $SD_{\text{elax}} = 137$ ms) and 20° ($M_{\text{fear}} = 546$ ms; $SD_{\text{fear}} = 106$ ms; $M_{\text{relax}} = 578$ ms; $SD_{\text{relax}} = 154$ ms), which did not present differences between them.

3.4 Peripheral task - target perception accuracy

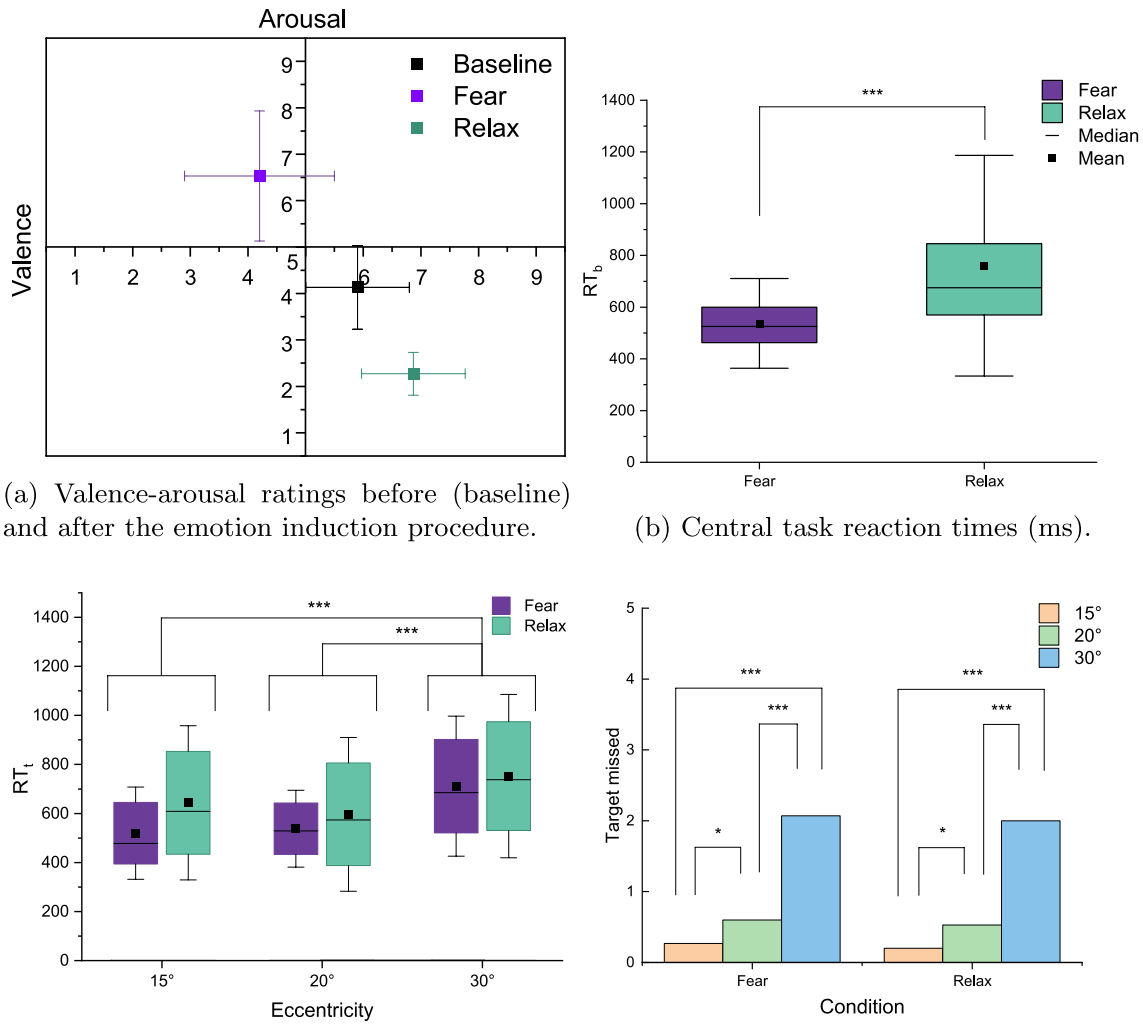
The results of the Mann–Whitney U test did not highlight significant differences in the number of targets missed between the two conditions for each eccentricity level [($U_{15} = 106.5$; $Z = -0.384$; $p > 0.05$); ($U_{20} = 105$; $Z = -0.363$; $p > 0.05$); ($U_{30} = 106$; $Z = -0.274$; $p > 0.05$)]. Therefore, we proceeded with a Wilcoxon signed-rank test to explore differences between the three eccentricity levels, independently from the experimental condition. Results showed that the number of targets perceived differed significantly between the three eccentricity levels. In particular, participants missed more targets at 30° of eccentricity ($M = 2.03$), compared to both targets presented at 15° ($M = 0.23$; $Z = -4.19$; $p < 0.001$) and 20° ($M = 0.57$; $Z = -4.021$; $p < 0.001$), which also show statistically significant differences between them ($Z = -2.077$; $p < 0.038$). Concerning the years since the driving license was obtained, no significant effects have been found on the central and peripheral tasks' measures.

4 Discussion

The research works available on the interaction between emotions, driving behavior, and attention is mainly focused on traffic-related attributes and present a heterogeneous pool of MIP. The results obtained in the presented study allowed us to introduce a new methodology to induce specific emotional responses, allowing us to have an insight into the effect that two clearly distinct emotional states have on a divided attention task. As visible in Fig. 4a, the analysis of the valence and arousal rates certified that we effectively induced two different emotional responses, characterized by a slightly negative valence and high arousal for the fear

Table 1 Descriptive statistics related to the central task (RT_b in ms) and the peripheral task (RT_t in ms and target perception accuracy)

	Central task		15° targets			20° targets			30° targets		
	RT_b		RT_t		Missed	RT_t		Missed	RT_t		Missed
Condition	*M*	*SD*	*M*	*SD*	*M*	*M*	*SD*	*M*	*M*	*SD*	*M*
Fear	537	116	508	93.9	0.27	546	106	0.6	718	180	2.07
Relax	760	284	595	137	0.2	578	154	0.53	732	200	2



(a) Valence-arousal ratings before (baseline) and after the emotion induction procedure.

(b) Central task reaction times (ms).

(c) Peripheral task reaction times (ms).

(d) Peripheral task missed targets.

Fig. 4 Data related to the experiment measures, including participants' emotional response, reaction times for the central and peripheral task, and target perception accuracy (***$p < 0.001$; *$p < 0.05$)

condition as opposed to positive valence and low arousal for the relax condition. The two emotional states were induced using immersive VR environments, allowing participants to seamlessly carry out the entire experiment without removing the headset and facilitating the maintenance of the elicited emotional state for the whole duration of the experiment. To the best of our knowledge, this is one of the first experimental works on the topic carried out entirely in VR and may represent a good starting point for future works focused on exploring the effects of a wider range of emotional states on drivers' attention.

The experimental task developed for this study allowed us to explore if and how two different emotional states can affect the way drivers divide their attention between a central driving-related task and a peripheral visual task. Specifically, the central task consisted of a driving-related action widely used in studies on the topic (i.e., a braking task following a leading vehicle), accompanied by a simultaneous peripheral task capable of providing information on two very important aspects: the horizontal extension of the driver's field of view, and the role it plays on the reaction times to perceived stimuli as a function not only of different eccentricities but also of the emotional state experienced by the driver.

The analysis of results revealed a significant effect of the emotional state of the participants on the reaction times related to the central braking task. On the contrary, drivers' emotions did not significantly affect the perception and the reaction to peripheral stimuli. As shown in Fig. 4b, scared drivers reacted significantly faster than relaxed drivers, highlighting the importance that the driver's level of activation seems to have on a driving-related task, where a level of

medium-high activation seems to be preferable to a state of greater relaxation that could appear to be even counterproductive in certain situations.

The goal of this study was not only to assess drivers' divided attention performance depending on different emotional responses, but also to assess the extent of a driver's visual field and how increasing eccentricity of a visual target affects the accuracy of the driver's perception and the speed of its reaction in an immersive VR driving simulation.

As anticipated, the reaction times in response to peripheral targets did not highlight a significant effect of the drivers' emotional state. Nevertheless, as visible in Fig. 4c, relaxed drivers presented systematically slower responses, even if not statistically significant, suggesting that an acceptable level of activation is nonetheless functional in a driving situation, particularly in contexts of divided attention such as the one treated in the current experimental task. Still, the analysis of the results revealed significant differences depending on the three eccentricity values considered. Participants' reaction times in response to targets presented at 15° and 20° of eccentricity did not show significant differences between them, while targets presented at 30° of eccentricity significantly differed from data related to all the other targets, revealing slower responses independently from the emotional state elicited. Moreover, when considering the accuracy with which participants effectively detected peripheral targets, results showed a decrease in accuracy as eccentricity increased. Figure 4d shows how the highest number of missed targets was found in targets presented at 30° of eccentricity, where participants' missed an average of two out of ten targets, a result that significantly differed from the other two eccentricity values. In this case, a significant difference was observed also between targets presented at 20° and 15° of eccentricity, with a slightly higher number of targets missed at 20°.

The developed methodology and the results obtained may represent an important starting point for the development of innovative and more precise ADAS systems, capable of taking into account the reaction capacity of a driver as a function of the position of an object in the surrounding environment. Furthermore, VR simulations are now a common tool during the development and testing of driver assistance systems (Gelder and Paardekooper 2017; Clement et al. 2022; Siebke et al. 2023). Previous experiments investigated the impact of distance, eccentricity, and time of visibility on the accuracy of perceiving visual targets within immersive virtual environments (Dozio et al. 2023). The results obtained provided reference measures to understand the relationship between these factors and perception accuracy. The present study allows us to broaden the scope by incorporating additional factors related to the emotional sphere and reaction speed. By considering the interplay between emotional states, reaction times, and perception accuracy, the current research work further explored the intricate components influencing visuospatial attention within immersive VR, achieving a heightened level of detail in characterizing the complex dynamics involved and expanding our understanding of the multifaceted aspects that must be considered while using VR as a testing tool in contexts where visuospatial attention and visual perception are involved.

5 Conclusions

The emotional responses elicited differed in terms of valence and arousal which significantly affected the way people reacted to the central task. On the contrary, the emotional state did not affect the performance of the peripheral task, which revealed instead a significant effect of the eccentricity at which the visual stimuli were presented, influencing both the accuracy of targets' perception and the reaction times. Although the emotional state did not influence the peripheral task, the results obtained offer a useful measure of the role that the eccentricity of a visual target can have on the accuracy with which it is perceived, and on the time interval within which a driver is able to react to it. Furthermore, the research works available on the effect that emotions have on driving behavior and drivers' attention include a wide range of emotional responses, but fail to provide a consistent MIP throughout all the different works, providing heterogeneous and sometimes contradicting results. Future development should try to apply the methodology presented in this paper expanding the range of emotional responses, also considering emotional responses that differ only in one dimension (e.g., same valence, different arousal), in order to obtain comparable results that might reveal different interactions with the considered measures. Finally, the current study relied on simplified interactions with the driving environment. Future works will aim to explore the topics of emotions and attention while driving in even more immersive and ecologically valid simulation contexts (e.g., using a pedal for the braking actions and buttons on the steering wheel for secondary tasks' interaction), ensuring a more natural interaction with the vehicle and the driving actions performed.

Author contributions All authors conceived the experiment. ND conducted the experiment and analyzed the results. MB and FF supervised the project. All authors reviewed and approved the manuscript.

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

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Abdu R, Shinar D, Meiran N (2012) Situational (state) anger and driving. Transport Res F: Traffic Psychol Behav 15(5):575–580. https://doi.org/10.1016/j.trf.2012.05.007

Adam JJ, Davelaar EJ, Van Der Gouw A, Willems P (2008) Evidence for attentional processing in spatial localization. Psychol Res 72(4):433–442. https://doi.org/10.1007/s00426-007-0126-2

Ball KK, Beard BL, Roenker DL, Miller RL, Griggs DS (1988) Age and visual search: expanding the useful field of view. J Opt Soc Am A 5(12):2210. https://doi.org/10.1364/josaa.5.002210

Ball KK, Owsley C, Sloane ME, Roenker DL, Bruni JR (1993) Visual attention problems as a predictor of vehicle crashes in older drivers. Invest Ophthalmol Vis Sci 34(11):3110–3123

Bradley MM, Lang PJ (1994) Measuring emotion: the self-assessment manikin and the semantic differential. J Behav Ther Exp Psychiatry 25(1):49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Cao S, Nandakumar K, Babu R, Thompson B (2020) Game play in virtual reality driving simulation involving head-mounted display and comparison to desktop display. Virtual Real 24:503–513. https://doi.org/10.1007/s10055-019-00412-x

Carrasco M, Evert DL, Chang I, Katz SM (1995) The eccentricity effect: target eccentricity affects performance on conjunction searches. Percept Psychophys 57(8):1241–1261. https://doi.org/10.3758/BF03208380

Carrasco M, McElreel B, Denisova K, Giordano AM (2003) Speed of visual processing increases with eccentricity. Nat Neurosci 6(7):699–700. https://doi.org/10.1038/nn1079

Chan M, Singhal A (2015) Emotion matters: implications for distracted driving. Saf Sci 72:302–309. https://doi.org/10.1016/j.ssci.2014.10.002

Clay OJ, Wadley VG, Edwards JD, Roth DL, Roenker DL, Ball KK (2005) Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: current and future implications. Optom Vis Sci 82(8):724–731. https://doi.org/10.1097/01.opx.0000175009.08626.65

Clement P, Veledar O, Könczöl C, Danzinger H, Posch M, Eichberger A, Macher G (2022) Enhancing acceptance and trust in automated driving trough virtual experience on a driving simulator. Energies. https://doi.org/10.3390/en15030781

Cutello CA, Gummerum M, Hanoch Y, Hellier E (2021) Evaluating an intervention to reduce risky driving behaviors: taking the fear out of virtual reality. Risk Anal 41(9):1662–1673. https://doi.org/10.1111/risa.13643

Deffenbacher JL, Oetting ER, Lynch RS (1994) Development of a driving anger scale. Psychol Rep 74(1):83–91. https://doi.org/10.2466/pr0.1994.74.1.8

Deffenbacher JL, Lynch RS, Oetting ER, Swaim RC (2002) The driving anger expression inventory: a measure of how people express their anger on the road. Behav Res Ther 40(6):717–737. https://doi.org/10.1016/S0005-7967(01)00063-8

Deffenbacher JL, Deffenbacher DM, Lynch RS, Richards TL (2003) Anger, aggression, and risky behavior: a comparison of high and low anger drivers. Behav Res Ther 41(6):701–718. https://doi.org/10.1016/S0005-7967(02)00046-3

DePasquale JP, Geller ES, Clarke SW, Littleton LC (2001) Measuring road rage: development of the propensity for angry driving scale. J Safety Res 32(1):1–16. https://doi.org/10.1016/S0022-4375(00)00050-5

Diemer J, Alpers GW, Peperkorn HM, Shiban Y, Mühlberger A (2015) The impact of perception and presence on emotional reactions: a review of research in virtual reality. Front Psychol. https://doi.org/10.3389/fpsyg.2015.00026

Dingus TA, Guo F, Lee S, Antin JF, Perez M, Buchanan-King M, Hankey J (2016) Driver crash risk factors and prevalence evaluation using naturalistic driving data. Proc Natl Acad Sci 113(10):2636–2641. https://doi.org/10.1073/pnas.1513271113

Dominguez J, Campillo J, Campo-Landines K, Contreras-Ortiz SH (2022) Impact of emotional states on the effective range of electric vehicles. J Ambient Intell Humaniz Comput. https://doi.org/10.1007/S12652-022-04410-X

Dozio N, Marcolin F, Scurati GW, Nonis F, Ulrich L, Vezzetti E, Ferrise F (2021) Development of an affective database made of interactive virtual environments. Sci Rep 11(1):1–10. https://doi.org/10.1038/s41598-021-03380-y

Dozio N, Marcolin F, Scurati GW, Ulrich L, Nonis F, Vezzetti E, Marsocci G, La Rosa A (2022) A design methodology for affective Virtual Reality. Int J Hum-Comput Stud 162:102791. https://doi.org/10.1016/j.ijhcs.2022.102791

Dozio N, Rozza L, Lukasiewicz MS, Colombo A, Ferrise F (2023) Localization and Prediction of Visual Targets' Position in Immersive Virtual Reality. PRESENCE: Virtual and Augmented Reality, 1–17 https://doi.org/10.1162/pres_a_00373

Edwards DC, Goolkasian PA (1974) Peripheral vision location and kinds of complex processing. J Exp Psychol 102(2):244. https://doi.org/10.1037/h0035859

Edwards JD, Ross LA, Wadley VG, Clay OJ, Crowe M, Roenker DL, Ball KK (2006) The useful field of view test: normative data for older adults. Arch Clin Neuropsychol 21(4):275–286. https://doi.org/10.1016/j.acn.2006.03.001

European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport: Annual statistical report on road safety in the EU 2020 (2021)

Faul F, Erdfelder E, Lang A-G, Buchner A (2007) G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods 39(2):175–191. https://doi.org/10.3758/BF03193146

Finucane AM (2011) The effect of fear and anger on selective attention. Emotion 11(4):970–974. https://doi.org/10.1037/a0022574

Gelder E, Paardekooper J-P (2017) Assessment of automated driving systems using real-life scenarios. In: 2017 IEEE Intelligent Vehicles Symposium (IV), pp. 589–594. https://doi.org/10.1109/IVS.2017.7995782

Gerritsen C, Frischen A, Blake A, Smblek D, Eastwood JD (2008) Visual search is not blind to emotion. Percept Psychophys 70(6):1047–1059. https://doi.org/10.3758/PP.70.6.1047

Huo F, Gao R, Sun C, Hou G (2022) Age differences in hazard perception of drivers: the roles of emotion. Front Psychol 13(June):1–11. https://doi.org/10.3389/fpsyg.2022.867673

Jallais C, Gilet A-L (2010) Inducing changes in arousal and valence: comparison of two mood induction procedures. Behav Res Methods 42(1):318–325. https://doi.org/10.3758/BRM.42.1.318

Jallais C, Gabaude C, Paire-Ficout L (2014) When emotions disturb the localization of road elements: effects of anger and sadness. Transp Res Part F: Traffic Psychol Behav 23:125–132. https://doi.org/10.1016/j.trf.2013.12.023

Jeon M (2016) Don't cry while you're driving: sad driving is as bad as angry driving. Int J Hum-Comput Interact 32(10):777–790. https://doi.org/10.1080/10447318.2016.1198524

Jeon M, Walker BN (2011) What to detect? Analyzing factor structures of affect in driving contexts for an emotion detection and regulation system. Proceedings of the Human Factors and Ergonomics Society, 1889–1893 https://doi.org/10.1177/1071181311551393

Jeon M, Zhang W (2013) Sadder but Wiser? Effects of Negative Emotions on Risk Perception, Driving Performance, and Perceived Workload. In: Proceedings of the human factors and ergonomics society, pp 1849–1853. https://doi.org/10.1177/1541931213571413

Jones MP, Chapman P, Bailey K (2014) The influence of image valence on visual attention and perception of risk in drivers. Accid Anal Prev 73:296–304. https://doi.org/10.1016/j.aap.2014.09.019

Kadoya Y, Watanapongvanich S, Khan MSR (2021) How is emotion associated with driving speed? A study on taxi drivers in Japan. Transp Res Part F: Traffic Psychol Behav 79:205–216. https://doi.org/10.1016/j.trf.2021.04.020

Kuhbandner C, Hanslmayr S, Maier MA, Pekrun R, Spitzer B, Pastötter B, Bäuml K-H (2009) Effects of mood on the speed of conscious perception: behavioural and electrophysiological evidence. Soc Cogn Affect Neurosci 4(3):286–293. https://doi.org/10.1093/scan/nsp010

Lamanuzzi M, Di Antonio JA, Foiadelli F, Longo M, Labombarda A, Dozio N, Ferrise F (2020) Analysis of energy consumption in an electric vehicle through virtual reality set-up. In: 2020 AEIT international annual conference (AEIT), pp 1–5. IEEE

Lewis I, Watson B, Tay R, White KM (2007) The role of fear appeals in improving driver safety: a review of the effectiveness of fear-arousing (threat) appeals in road safety advertising. Int J Behav Consult Ther 3(2):203–222. https://doi.org/10.1037/h0100799

Lewis I, Watson B, White KM (2008) An examination of message-relevant affect in road safety messages: should road safety advertisements aim to make us feel good or bad? Transport Res F: Traffic Psychol Behav 11(6):403–417. https://doi.org/10.1016/J.TRF.2008.03.003

Liu Y, Wang X, Chen L, Liu S, Han J, Shi H, Zhong F (2022) Driver's visual attention characteristics and their emotional influencing mechanism under different cognitive tasks. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph19095059

Lu J, Xie X, Zhang R (2013) Focusing on appraisals: how and why anger and fear influence driving risk perception. J Saf Res 45:65–73. https://doi.org/10.1016/j.jsr.2013.01.009

Malone S, Brünken R (2021) Hazard perception, presence, and simulation sickness-a comparison of desktop and head-mounted display for driving simulation. Front Psychol 12:647723. https://doi.org/10.3389/fpsyg.2021.647723

Öhman A, Flykt A, Esteves F (2001) Emotion drives attention: detecting the snake in the grass. J Exp Psychol Gen 130(3):466–478. https://doi.org/10.1037/0096-3445.130.3.466

Owsley C (2013) Visual processing speed. Vision Res 90:52–56. https://doi.org/10.1016/J.VISRES.2012.11.014

Pêcher C, Lemercier C, Cellier J-M (2009) Emotions drive attention: effects on driver's behaviour. Saf Sci 47(9):1254–1259. https://doi.org/10.1016/j.ssci.2009.03.011

Pessoa L (2008) On the relationship between emotion and cognition. Nat Rev Neurosci 9(2):148–158. https://doi.org/10.1038/nrn2317

Precht L, Keinath A, Krems JF (2017) Effects of driving anger on driver behavior-results from naturalistic driving data. Transport Res F: Traffic Psychol Behav 45:75–92. https://doi.org/10.1016/j.trf.2016.10.019

Rogé J, Kielbasa L, Muzet A (2002) Deformation of the useful visual field with state of vigilance, task priority, and central task complexity. Percept Motor Skills 95(1):118–130. https://doi.org/10.2466/pms.2002.95.1.118

Sanders AF (1970) Some aspects of the selective process in the functional visual field. Ergonomics 13(1):101–117. https://doi.org/10.1080/00140137008931124

Scherer KR, Schorr A, Johnstone T (2001) Appraisal processes in emotion: Theory, methods, research. Oxford University Press, Oxford

Sekuler R, Ball K (1986) Visual localization: age and practice. J Opt Soc Am A 3(6):864. https://doi.org/10.1364/josaa.3.000864

Siebke C, Mai M, Prokop G (2023) What do traffic simulations have to provide for virtual road safety assessment? Human error modeling in traffic simulations. IEEE Trans Intell Transp Syst 24(2):1419–1436. https://doi.org/10.1109/TITS.2022.3220961

Smith CA, Lazarus RS et al (1990) Emotion and adaptation. Handbook of personality: Theory and research, vol 21, pp 609–637

Soares SC, Esteves F, Flykt A (2009) Fear, but not fear-relevance, modulates reaction times in visual search with animal distractors. J Anxiety Disord 23(1):136–144. https://doi.org/10.1016/j.janxdis.2008.05.002

Staugaard CF, Petersen A, Vangkilde S (2016) Eccentricity effects in vision and attention. Neuropsychologia 92:69–78. https://doi.org/10.1016/j.neuropsychologia.2016.06.020

Steinhauser K, Leist F, Maier K, Michel V, Pärsch N, Rigley P, Wurm F, Steinhauser M (2018) Effects of emotions on driving behavior. Transp Res Part F: Psychol Behav 59:150–163. https://doi.org/10.1016/j.trf.2018.08.012

Stephens AN, Lennon A, Bihler C, Trawley S (2019) The measure for angry drivers (MAD). Transport Res F: Traffic Psychol Behav 64:472–484. https://doi.org/10.1016/j.trf.2019.06.002

Stewart T (2022) Overview of Motor Vehicle Crashes in 2020 (Report No. DOT HS 813 266). National Highway Traffic Safety Administration (March)

Westermann R, Spies K, Stahl G, Hesse FW (1996) Relative effectiveness and validity of mood induction procedures: a meta-analysis. Eur J Soc Psychol 26(4):557–580. https://doi.org/10.1002/(SICI)1099-0992(199607)26:4<557::AID-EJSP769>3.0.CO;2-4

Zepf S, Hernandez J, Schmitt A, Minker W, Picard RW (2020) Driver emotion recognition for intelligent vehicles: a survey. ACM Comput Surv 53(3):1–30. https://doi.org/10.1145/3388790

Zhang Q, Qu W, Ge Y (2022) The effect of anger on pedestrian avoidance in a simulated driving task. Accid Anal Prev 171:106664. https://doi.org/10.1016/j.aap.2022.106664