Perceptual Load in Different Regions of the Visual Scene and Its Relevance for Driving

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Objective: The aim of this study was to better understand the role played by perceptual load, at both central and peripheral regions of the visual scene, in driving safety.

Background: Attention is a crucial factor in driving safety, and previous laboratory studies suggest that perceptual load is an important factor determining the efficiency of attentional selectivity. Yet, the effects of perceptual load on driving were never studied systematically.

Method: Using a driving simulator, we orthogonally manipulated the load levels at the road (central load) and its sides (peripheral load), while occasionally introducing critical events at one of these regions.

Results: Perceptual load affected driving performance at both regions of the visual scene. Critically, the effect was different for central versus peripheral load: Whereas load levels on the road mainly affected driving speed, load levels on its sides mainly affected the ability to detect critical events initiating from the roadsides. Moreover, higher levels of peripheral load impaired performance but mainly with low levels of central load, replicating findings with simple letter stimuli.

Conclusion: Perceptual load has a considerable effect on driving, but the nature of this effect depends on the region of the visual scene at which the load is introduced.

Application: Given the observed importance of perceptual load, authors of future studies of driving safety should take it into account. Specifically, these findings suggest that our understanding of factors that may be relevant for driving safety would benefit from studying these factors under different levels of load at different regions of the visual scene.

Keywords: selective attention, perceptual load, driving distraction, driving simulator

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INTRODUCTION

Selective attention—the ability to grant processing priority to relevant information over irrelevant information—is one of the main factors involved in vehicle collisions (e.g., Treat et al., 1979; Utter, 2001; See Trick, Enns, Mills, & Vavrik, 2004, for a review). It was estimated that the involvement of inattention in car accidents is about 25% to 37% of total car collisions (e.g., Stutts, Reinfurt, Staplin, & Rodgman, 2001; Sussman, Bishop, Madnick, & Walter, 1985), and recently, Beanland, Fitzharris, Young, and Lenné (2013) analyzed data of 856 crashes and reported that 57.6% were evidently related to driver inattention. Inadequate performance that is due to a failure of attention may be caused by either an ineffective attentional selectivity—the attraction of attention by irrelevant objects or events—or a too-stringent selectivity—failure to attend relevant but unexpected events. Both cases may have severe consequences for driving safety (see Engström et al., 2013; Regan, Hallett, & Gordon, 2011; and Wickens & Horrey, 2009, for a discussion of different types of attention failure).

The concept of perceptual load was offered as an account for these seemingly contradicting findings that attentional selectivity can be either too high or too low (e.g., Lavie, 1995). According to the load theory, conditions of high perceptual load result in high attentional selectivity, because resources are fully consumed by task-relevant processing and none is left for perceiving irrelevant information. In contrast, conditions of low perceptual load result in low attentional selectivity, because unconsumed resources inevitability spill over to perceive irrelevant information. Several studies demonstrated the importance of perceptual load in determining performance under highly controlled conditions with simple stimuli, such as letters (e.g., Beck & Lavie, 2005; Lavie & Cox, 1997; Lavie & de Fockert, 2003).

The relations between perceptual load and attentional selectivity seem to be also relevant to driving because driving takes place at varying load levels that may change rapidly and dramatically. In models of supervisory control in driving, drivers' scanning behavior, which aims to bring critical information into focus, is guided by bottom-up as well as top-down factors. For example, the SEEV (saliency effort expectancy value) model (e.g., Horrey, Wickens, & Consalus, 2006; Wickens & Horrey, 2009) suggests that the salience of events and scanning efforts are bottom-up factors, whereas events' expectancy based on information bandwidth (i.e., event rate) and the value of the source of information to the task are top-down factors. The concept of perceptual load, particularly in its most common operationalization as the number of items, seems relevant for both bottom-up and top-down factors. For instance, an object that is surrounded by many other objects is likely less salient than an isolated object. Other factors, such as object-environment similarity, also determine saliency (e.g., Steelman, McCarley, & Wickens, 2011), though here only items' number was manipulated. Additionally, the concept of perceptual load is tightly related to the concept of expectancy because the SEEV model defines expectancy as event rate. Thus, the higher the rate of events at a given region, the higher the perceptual load at that region and the more often this region will be scanned.

Initial studies of perceptual load under controlled conditions were constrained to load manipulation at central regions of the visual field. In a recent study, we extended this investigation to also include load manipulation at peripheral regions (Marciano & Yeshurun, 2011). Using simple letter stimuli, we manipulated orthogonally load levels at both central (task-relevant) and peripheral (task-irrelevant) regions. The findings of this study underscore the importance of such combined manipulations of central and peripheral load because their effects interacted: Increasing peripheral load deteriorated performance but only with low levels of central load. In the current study, we examined whether a similar combined manipulation of central and peripheral load would also be relevant to performance under less controlled conditions that are more similar to everyday life, such as driving. Authors of previous studies of driving did not take into account, in a systematic manner, the variable of perceptual load, even though as described earlier, theory and evidence collected in more controlled settings suggest that perceptual load is an important factor. Some researchers did refer to road characteristics (e.g., Horberry, Anderson, Regan, Triggs, & Brown, 2006; Östlund, Nilsson, Törnros, & Forsman, 2006; Pammer & Blink, 2013; Stinchcombe & Gagnon, 2010; Young et al., 2009) but did not systematically manipulate perceptual load conditions in various regions of the visual scene.

Other researchers referred directly to the notion of perceptual load but did not manipulate the load levels of the simulated driving environment (Redenbo & Lee, 2009; Tan & Lee, 2009). These studies employed a dual-task paradigm, in which the drivers had to perform an additional task with simple stimuli (e.g., digits, squares) while driving in a simulator. The load manipulation, which was introduced only within the secondary task, did not affect driving-related performance. Hence, prior research provides only a very limited, often indirect, view of the role played by perceptual load in driving safety.

To test whether the concept of perceptual load can predict drivers' behavior, we employed a similar manipulation of load to that tested in controlled experiments with a setting that resembles real life in a driving simulator. We systematically manipulated the load levels at different regions of the visual scene: central load—load levels on the road—and peripheral load—load levels on the sides of the road. This design resulted in four load combinations: (a) low load in both regions (LL), (b) high central load with low peripheral load (HL), (c) low central load with high peripheral load (LH), and (d) high load in both regions (HH). Occasionally, critical events occurred on the road (e.g., a sudden braking of the car in front) or were initiated from the sides of the road (e.g., a pedestrian who suddenly crossed the road). Driving performance was measured using several different measurements: ongoing measurements, such as vehicle speed, and events-based measurements, such as reaction time (RT) to the critical events. This design allowed a more comprehensive evaluation of the effects of perceptual load on driving because we could examine these effects separately for each combination of load level, load region, and region of critical event.

If perceptual load has similar effects on performance in a driving simulator, as it has under highly controlled settings, the results found here should be similar to those found before (Marciano & Yeshurun, 2011). Specifically, we expect both types of load—central and peripheral—to affect driving. Additionally, according to the load theory, an interaction should emerge: Peripheral load should affect performance only when the levels of central load are low, because with high central load, no resources should be allocated to the periphery thus load levels should not matter. An interaction is also expected based on the SEEV model because as central load increases, expectations regarding this central region also increase, and given that the road is likely assigned a higher value than its sides, the periphery should be scanned less often and peripheral load should matter less.

METHOD

Participants

Thirty-eight students from the University of Haifa participated in the study (15 women; age range = 22–31, mean = 25.6) for a monetary reward. All participants had driving experience of at least five years.

Apparatus

The study took place in a partial driving simulator using STISIM Drive® software on a PC computer with INTEL Duo Core E8400 processor and NVIDIA Quadro FX5600 graphic card. A Logitech steering system, which included steering wheel and gas and brake pedals, was used (Figure 1). The participant sat 2.5 m in front of a wide screen (2.3 × 3 m) subtending 62° of visual angle. A speaker providing background sounds was placed behind the participant.

Driving Scenarios

Two different 23-km-long scenarios simulated a suburban road with two lanes in each direction separated by a road median. Each scenario consisted of four load conditions, with order balanced between the scenarios, involving different combinations of central and peripheral load levels (Figure 2): (a) LL, (b) HL, (c) LH, and (d) HH.

Figure 1. The experimental setup. The participant set in a clerical chair, holding the wheel, and the scenario was presented on a wide screen in front of her.

Central load was manipulated via the number and congestion of vehicles. Peripheral load was manipulated via the number and spacing of standing and moving pedestrians, buildings, and parked vehicles (Table 1). Each scenario included 16 critical events, of which 8 occurred on the road (central events) and 8 were initiated from the sides of the road (peripheral events, Table 2). All events were designed to lead to a collision unless corrective action is taken.

Procedure

Each participant took part in one practice scenario and two different experimental scenarios; each took about half an hour. The practice scenario included three critical events, one on the road and two from its sides. To encourage the participants to drive at a speed that resembles driving in real life instead of slowing down unrealistically to prevent accidents, they were informed that they would receive a monetary bonus if they finished the session quickly but that each violation of traffic laws (including exceeding speed limit) would result in a monetary penalty. Thus, they were encouraged to drive as fast as possible without breaking the law. Out of the 38 participants, 1 received full bonus and the rest received partial or no

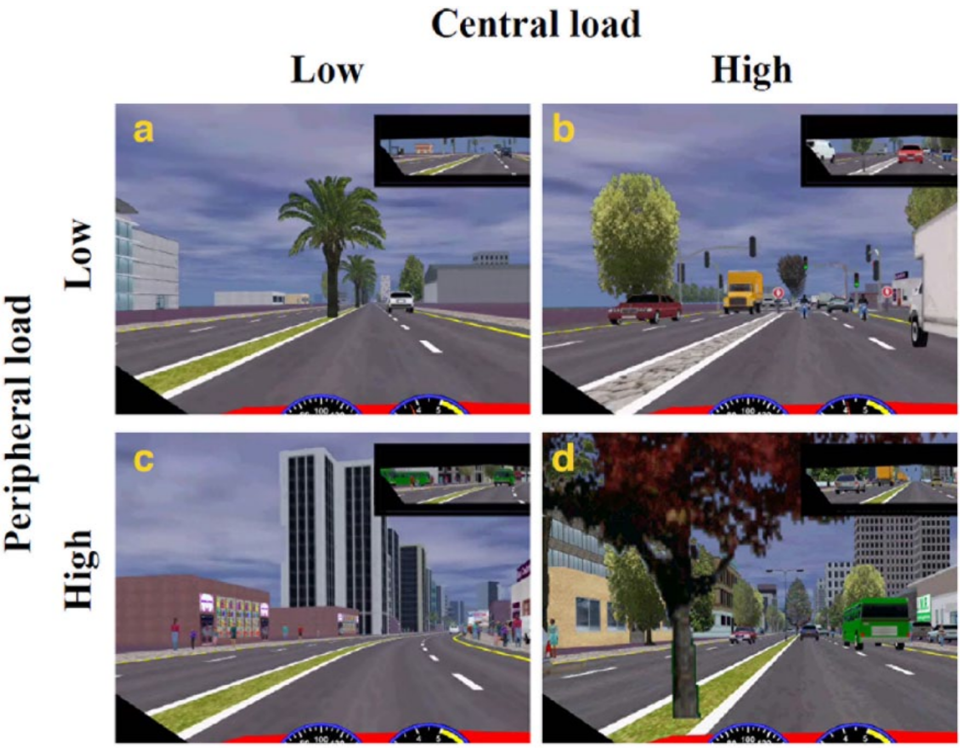

Figure 2. Illustrations of the four load conditions. (a) LL: Low load on both the road and its sides. (b) HL: High load on the road (central load), low load on the road's sides (peripheral load). (c) LH: Low central load, high peripheral load. (d) HH: High load on both regions.

TABLE 1: Load Manipulation According to the Region of Visual Scene (On the Road—Central—Vs. From Its Sides—Peripheral) and Level of Load (Low vs. High)

Region	Load Level	Entity	Mean Number per Kilometer
Central, right side	Low	Vehicles	4
Central, left side	Low	Vehicles	11
Central, right side	High	Vehicles	37
Central, left side	High	Vehicles	39
Peripheral, right side	Low	Pedestrians	5
Peripheral, left side	Low	Pedestrians	3
Peripheral, right side	High	Pedestrians	225
Peripheral, left side	High	Pedestrians	101
Peripheral, right side	Low	Buildings	9
Peripheral, left side	Low	Buildings	7
Peripheral, right side	High	Buildings	46
Peripheral, left side	High	Buildings	45
Peripheral, right side	Low	Parked vehicles	3
Peripheral, left side	Low	Parked vehicles	6
Peripheral, right side	High	Parked vehicles	14
Peripheral, left side	High	Parked vehicles	30

TABLE 2: Events Description per Scenario and Time to Collision (TTC)

Number	Region of Event	Entity	Event Description	TTC
8	Center	Car	The car in front of the driver suddenly braked or a car in an adjacent lane suddenly entered the driver's lane (always in front of the driver) and then braked	About 2.5 s
2	Periphery	Car	A car suddenly reversed from the sides into the road	About 2 s
2	Periphery	Car	A car suddenly entered the road from the sides	About 1 s
1	Periphery	Motorcycle	A motorcycle suddenly entered the road from the sides	About 1 s
2	Periphery	Pedestrian	A pedestrian suddenly crossed the road	About 2.5 s
1	Periphery	Dog	A dog suddenly crossed the road	About 2.5 s

bonus depending on their number of violations (range = 1–6 violations). The speed limit, indicated by a road sign, was 70 or 90 km/h.

Dependent Variables

Driving performance was analyzed using two groups of measurements.

Whole-scenario measurements. Measurements taken across the whole scenario (i.e., not specifically related to the preplanned events) included the following: (a) the vehicle's median speed, which is less sensitive than mean speed to periods in which the vehicle's speed is close to zero; (b) 90th-percentile speed, the speed value below which 90% of the speed observations were found, which reflects the ongoing tendency of the driver to adopt extreme speeds; and (c) mean number of collisions, which takes into account all the collisions that occurred for a given condition whether they were related to a critical event or not.

Responses to critical events. The following measurements are related to the preplanned critical events. (a) Proportion of collisions (the number of collisions divided by the total number of critical events in a given condition) includes only collisions that occurred up to 10 s after the occurrence of a critical event and therefore most likely were caused by the events. (b) RT refers to the time elapsed from event onset until the driver initiated a reaction. A reaction was defined as one of the following options: 1) a considerable change in the pressure on one of the pedals. Pedals' pressure was measured approximately every 13 ms, and the criterion for a change was a ratio of at least 1.4 between the current measurement, n, and its successive measurement, $n+1$. 2) Alternatively, a reaction could be defined as a complete lane changing to bypass the event. The reaction initiation was the moment at which a change in the vehicle's lateral position was registered. Cases in which it was impossible to pinpoint the time of reaction were excluded from the analysis, and so were cases in which no reaction was made and hence resulted in collision. (c) The distance that the vehicle advanced which was measured from the moment the event started until a response was made. This is a more complex measurement that takes into account the speed of the car as well as the driver's RT. Specifically, this measurement is the difference between the position of the vehicle when the critical event occurred and its position when the driver's first reaction was traced.

RESULTS

The various values of the statistical analyses are presented in tables to ensure a more concise report. Also note that unless otherwise stated, we present only results that were statistically significant ($p < .05$).

Whole-Scenario Measurements

We performed a two-way within-subjects ANOVA on the data sets of all the whole-scenario measurements, with central load (low vs. high)

TABLE 3: Significant Effects of the Whole-Scenario ANOVA (Central Load × Peripheral Load)

Measurement	*df*	*F*	*p*	η_p^2
Central load				
Median speed	1, 37	619.63	<.0001	.94
90th-percentile speed	1, 37	307.54	<.0001	.89
Number of collisions	1, 37	4.72	<.04	.11
Peripheral load				
Median speed	1, 37	52.41	<.0001	.59
90th-percentile speed	1, 37	202.55	<.0001	.84
Central Load × Peripheral Load				
Median speed	1, 37	31.79	<.0001	.46
90th-percentile speed	1, 37	123.03	<.0001	.77

and peripheral load (low vs. high) as variables (Table 3). Significant interactions were further explored using least significant difference post hoc analyses.

Speed measurements. The pattern of results was similar for both speed measurements (median and 90th percentile). The main effect of central load was significant (Figures 3a, 3b), and so was the main effect of peripheral load (Figures 3d, 3e). In both cases, the speed was faster with low than with high levels of load. These findings suggest that the manipulations of central and peripheral load were successful. The two-way interaction between these variables was also significant (Figures 4a, 4b). When the central load was low, slower speed was adopted with high than with low peripheral load. However, when the central load was high, this difference was eliminated with median speed and considerably reduced with 90th-percentile speed. These two-way interactions are similar to the interaction between central and peripheral load found in Marciano and Yeshurun (2011). There too, peripheral load affected performance only when the levels of central load were low.

Mean number of collisions. Only the main effect of central load was significant, showing more collisions with low than with high central load (Figure 3c). This finding might be due to the higher driving speed adopted with low central load.

Reactions to Critical Events

We performed a three-way within-subjects ANOVA on the data sets of the three critical events–related measurements, with the variables of central load (low vs. high), peripheral load (low vs. high), and event location (center vs. periphery) (Table 4).

Collisions proportion. The main effects of central and peripheral load were significant; collisions proportion was higher with low than with high central load (Figure 5a) but lower with low than with high peripheral load (Figure 5d). The former is likely due to the faster driving speed the participants adopted when the central load was low. The latter likely reflects the fact that with increased peripheral load, the scene was more cluttered. The additional clutter increased the difficulty of critical events' detection, resulting in increased probability of collisions. The main effect of event location was also significant. Collisions proportion was higher with peripheral events than with central events (Figure 6a). This finding is probably due to greater allocation of attentional resources to the road than to its sides. Of course, such resource allocation strategy is natural when driving, but evidently it also makes the sides of the road more vulnerable when a sudden event occurs.

Both two-way interactions, Central Load × Event Location (Figure 7a) and Peripheral Load × Event Location (Figure 8a), were significant. In both cases, the difference in collisions proportion between the different levels of load was significant only for peripheral events. The former interaction probably stemmed from the fact that driving speed was relatively low with high central load. This behavior helped the participants to

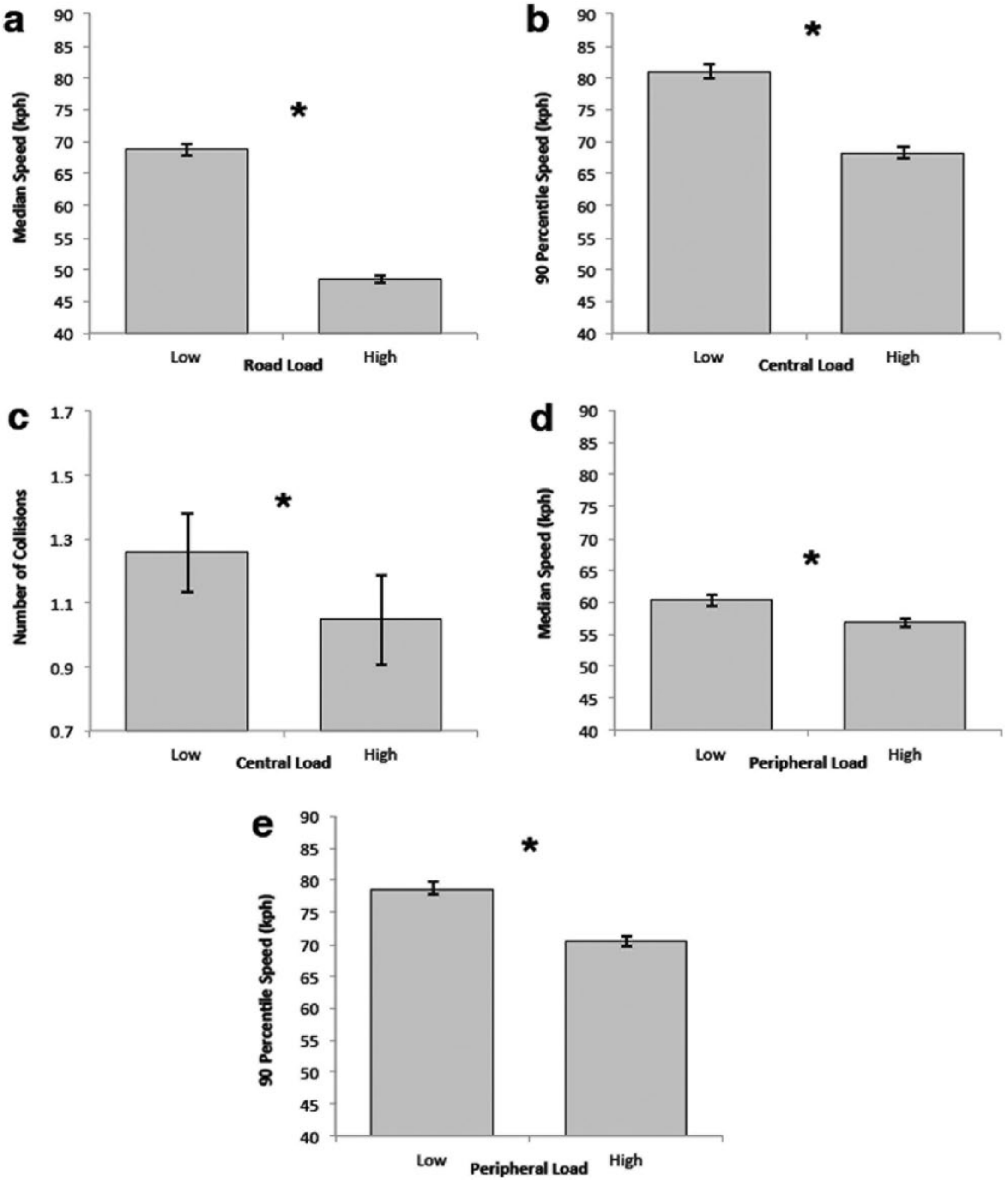

Figure 3. Whole-scenario measurements: (a) median speed, (b) 90th-percentile speed, and (c) number of collisions as a function of central load; (d) median speed and (e) 90th-percentile speed as a function of peripheral load. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

avoid collisions, which was particularly required for peripheral events, as they were initiated from a less attended region of the visual scene. Events occurring on the road were relatively easy to spot regardless of speed. The latter interaction most likely reflects the fact that the increased peripheral load decreased the ability to detect critical events initiated from the cluttered peripheral

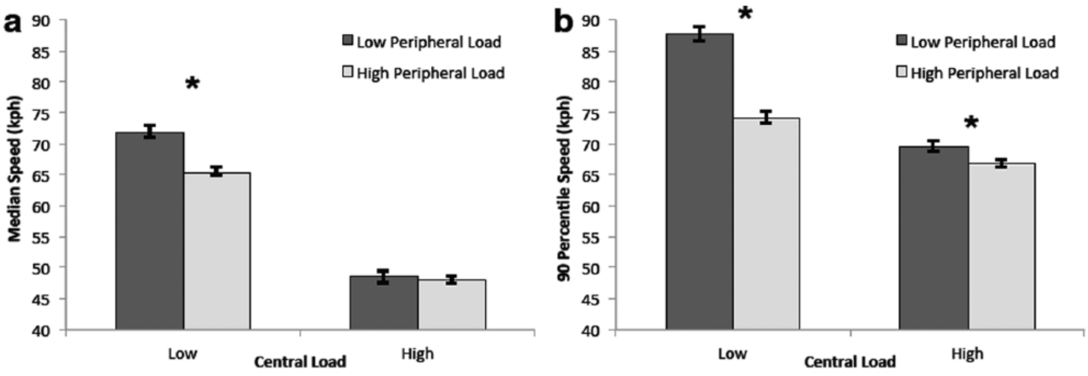

Figure 4. (a) Median speed and (b) 90th-percentile speed in the whole scenario as a function of central load and peripheral load. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

regions, to the extent that some of these events were missed altogether and ended in a collision. In contrast, central events were easy to detect regardless of peripheral load.

RT. Both main effects of central and peripheral load were significant; RT was longer with low than with high central load (Figure 5b) but shorter with low than with high peripheral load (Figure 5e). Again, the former is probably due to increased speed with low central load, and the latter likely reflects increased difficulty of events' detection with high peripheral load. The main effect of event location was also significant. RT was longer with peripheral events (Figure 6b), probably due to the greater allocation of attentional resources to the road than to its sides.

The two-way interaction between central and peripheral load was significant (Figure 9). RT was significantly longer with high peripheral load but only when the central load was low. This interaction is similar to that found in the whole-scenario analyses for the speed measurements and in our previous study (Marciano & Yeshurun, 2011). Both two-way interactions, Central Load × Event Location (Figure 7b) and Peripheral Load × Event Location (Figure 8b), were also significant. In both cases, the RT difference between the different load levels was significant only for peripheral events. The former interaction may be due to the fact that the slow driving speed with high central load helped the participants react faster, which was particularly required for the less attended peripheral events. The latter interaction probably reflects the decreased ability to detect critical peripheral events with high peripheral load, resulting in slowed RT. Finally, the three-way interaction between central load, peripheral load, and event location was significant (Figure 10a). The RT increase with peripheral events under high peripheral load was significant only when the central load was low. This finding is related to the interplay between central and peripheral load mentioned earlier.

Distance traveled until response. The main effect of central load was significant; a longer distance was traveled with low central load (Figure 5c), probably due to the faster driving speed adopted in this condition. The main effect of event location was also significant; a longer distance was traveled with peripheral events than with central events (Figure 6c). Again, this finding may reflect greater attention allocation to the central than to peripheral regions of the visual scene. The two-way interaction between central load and event location was significant (Figure 7c). The distance traveled was shorter with high than with low central load, reflecting the slower driving speed under high central load, but this difference was more pronounced for peripheral events, as they were harder to detect.

Finally, the three-way interaction between central load, peripheral load, and event location was significant (Figure 10b). The distance traveled until response to central events was significantly shorter with high peripheral load but only

TABLE 4: Significant Effects of the ANOVA (Central Load × Peripheral Load × Event Location) on Responses to Critical Events

Measurement	*df*	*F*	*p*	η_p^2
Central load				
Collisions proportion	1, 37	11.17	<.002	.23
RT	1, 37	26.47	<.0001	.42
Distance traveled	1, 37	211.51	<.0001	.85
Peripheral load				
Collisions proportion	1, 37	4.72	<.04	.11
RT	1, 37	6.32	<.02	.14
Event location				
Collisions proportion	1, 37	24.89	<.0001	.40
RT	1, 37	178.68	<.0001	.83
Distance traveled	1, 37	285.17	<.0001	.88
Central Load × Peripheral Load				
RT	1, 37	10.54	<.003	.22
Central Load × Event Location				
Collisions proportion	1, 37	4.29	<.05	.10
RT	1, 37	27.94	<.0001	.43
Distance traveled	1, 37	78.97	<.0001	.68
Peripheral Load × Event Location				
Collisions proportion	1, 37	12.27	<.002	.25
RT	1, 37	9.81	<.004	.21
Central Load × Peripheral Load × Event Location				
RT	1, 37	8.80	<.006	.19
Distance traveled	1, 37	7.36	<.02	.16

Note. RT = reaction time.

when central load was low. This difference in the pattern of interaction found with RT and distance is expected given that these two measurements are affected differently by the different driving-related factors. Although RT is also affected by driving speed, it is mainly mediated by the ability of the participants to detect the critical event, and this factor is most relevant for peripheral events. The distance traveled is affected by driving speed in a more direct manner: A car that is moving faster will advance a greater distance before response than will a slower car, even if RT is identical for both cars. Thus, the effect on distance was apparent when central load was low and the participants adopted a faster speed, and when detection was not a considerably limiting factor because the event occurred on the road. The distance traveled after the onset of peripheral events under low central load did not change as a function of peripheral load because the aforementioned RT increase for peripheral events nullified the effect of driving speed, resulting in no apparent change in distance.

DISCUSSION

Several studies demonstrated that perceptual load is a critical factor in determining performance under highly controlled conditions with simple stimuli, such as letters (see Lavie, 2001, for review). We examined whether the concept of perceptual load is also relevant under conditions that are closer to real life, like driving in a driving simulator. Effects of road characteristics that are related to perceptual load, like the number of cars on the road, were studied before (e.g., Edquist, Rudin-Brown, & Lenné,

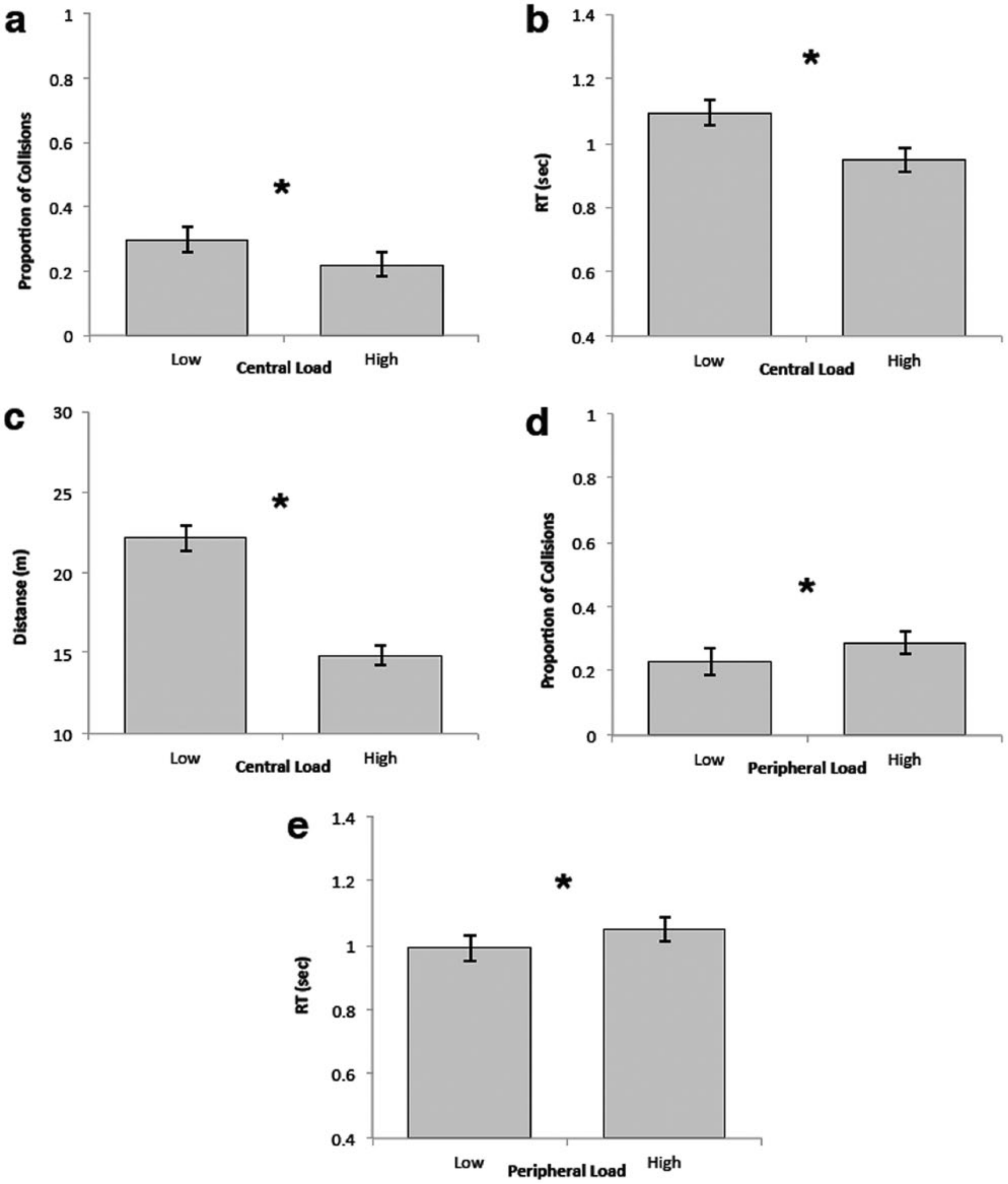

Figure 5. (a) Collisions proportion, (b) reaction time (RT), and (c) distance traveled until response as a function of central load; (d) collisions proportion and (e) RT as a function of peripheral load. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

2012; Stinchcombe & Gagnon, 2010) but not in a systematic manner. In this study, driving was evaluated under different combinations of load levels on the road and on its sides.

As was found in our previous study with simple stimuli (Marciano & Yeshurun, 2011), the degree of perceptual load and its location within the visual scene—central versus peripheral—also

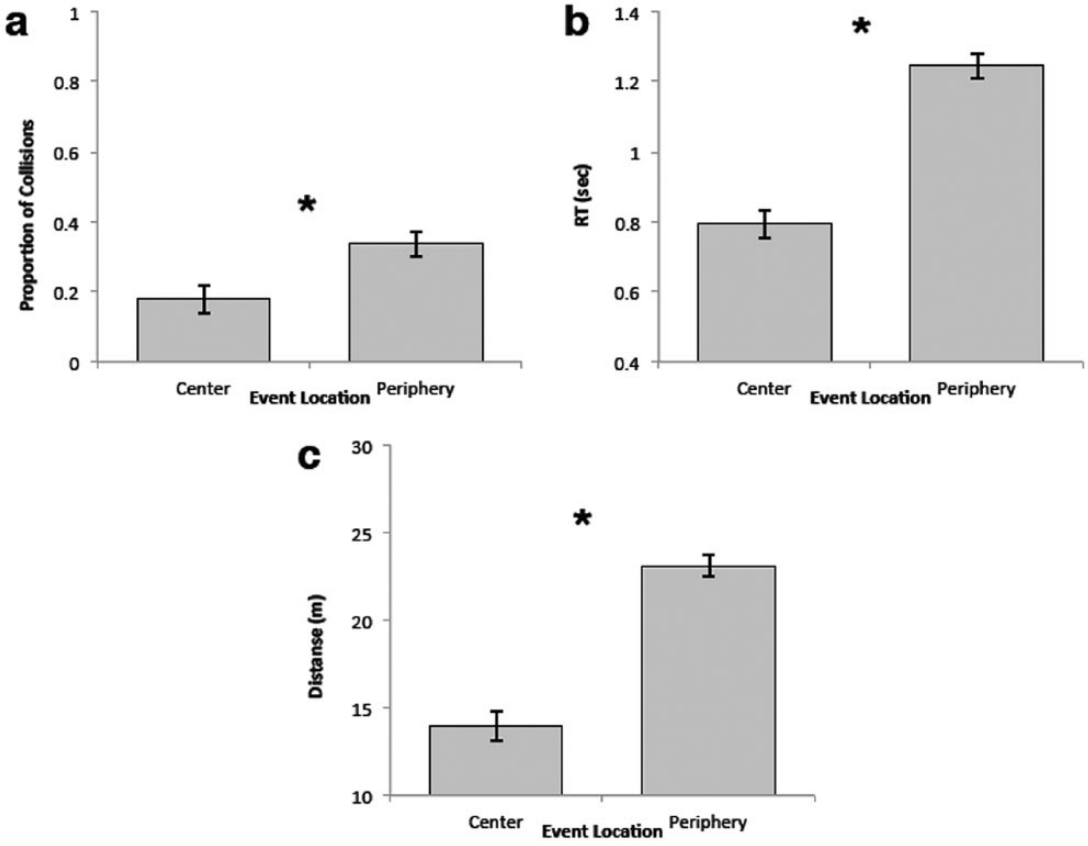

Figure 6. (a) Collisions proportion, (b) reaction time, and (c) distance traveled until response as a function of event location. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

played an important role in determining performance in the current study. Specifically, the behavioral measurement that was affected to the largest degree by perceptual load was driving speed. When perceptual load was low, particularly on the road, the participants drove faster. Apparently, they assumed that under low levels of load, they can maintain adequate driving performance even when driving fast. This driving strategy had considerable ramifications on the other measurements of driving performance, mainly with regard to peripheral events. With these events, when the level of central load was low, more collisions occurred, RT was slower, and the car traveled a greater distance from the onset of the event until response initiation. Adopting high driving speed when load levels were low was less detrimental with central events, probably because they were indeed easy to detect under the low–central load condition. Still, the danger involved in such speeding is evident in the finding that under low central load, the car traveled the greatest distance from the onset of the central event to the initiation of a response.

The level of peripheral load had a somewhat different effect on driving performance. Similar to the effect of central load, low levels of peripheral load encouraged the participants to drive faster, but this effect of peripheral load was modulated by the central load: It was larger with low than with high central load. Hence, the results in this more natural setting replicate those found in the more controlled setting employed in our previous study (Marciano & Yeshurun, 2011). However, because with high peripheral load, the detection of critical events, particularly, peripheral events, was considerably harder, the overall

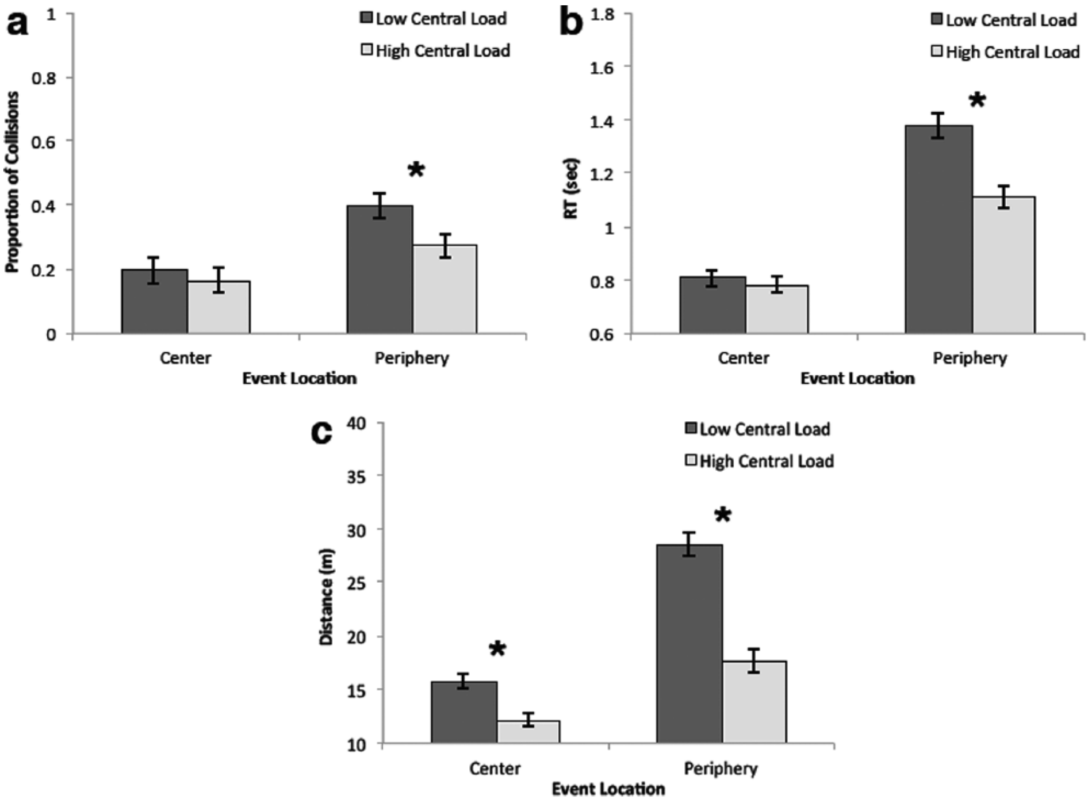

Figure 7. (a) Collisions proportion, (b) reaction time, and (c) distance traveled until response as a function of central load and event location. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

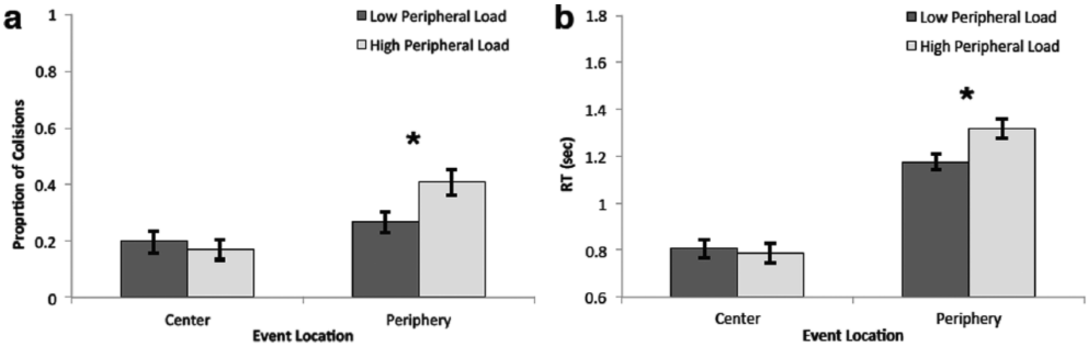

Figure 8. (a) Collisions proportion and (b) reaction time as a function of peripheral load and event location. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

effect of peripheral load on driving was different than that of central load. Specifically, in contrast to the central load conditions, higher proportion of collisions and longer RTs were found for peripheral events when the level of peripheral load was high than when it was low.

The two-way interaction (Central Load × Peripheral Load) that was found with both speed

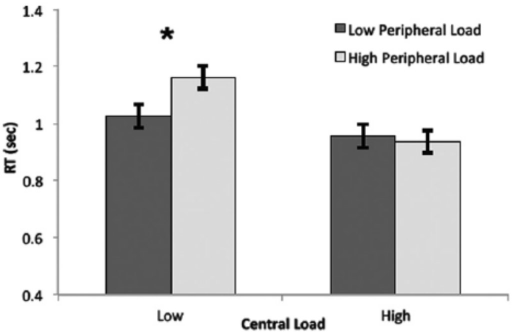

Figure 9. Reaction time to critical events as a function of central load and peripheral load. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

measurements and RT is similar to the corresponding interaction found in Marciano and Yeshurun (2011). The finding that increased central load reduced the effect of peripheral load is consistent with both the load theory (e.g., Lavie, 1995; Lavie & Cox, 1997) and the SEEV model (e.g., Wickens & Horrey, 2009), but their exact predictions are somewhat different. According to the load theory, when central load is high, central processing consumes all resources and none is left for the processing of peripheral information. Hence, according to the theory, with high central load, there should be no effect of peripheral load, as indeed was found with the measurements of median speed and RT. According to the SEEV model, with high central load, expectancy is higher and therefore more time will be spent scanning the central region, at the expense of peripheral scanning duration. Thus, this model also predicts a reduction in the effect of peripheral load with high central load. However, according to the model, scanning behavior is also affected by the value (relevancy) assigned to a region, and because while driving, the periphery is also relevant (though to a lesser degree than the central region), at least some scanning time should be devoted to the periphery. Hence, the model predicts that the effect of peripheral load should not be completely eliminated with high central load, as indeed was found with the measurement of 90th-percentile speed. The current findings, therefore, are not entirely consistent with any of these models.

It is important to note, however, that both models were not designed to account for all the various aspects of our study. The load theory assumes that peripheral information is not relevant and therefore it is not designed to deal with tasks, such as driving, in which the periphery may become relevant. The SEEV model is designed to predict scan pattern, which is important for some aspects of driving, such as hazard detection, but is less relevant for driving-related tasks that can be performed without focal vision, such as lane keeping (e.g., Horrey et al., 2006; Wickens & Horrey, 2009). That is, it was not designed to generate fine predictions with regard to many of the driving behaviors measured in this study. Developing a more comprehensive model is obviously a challenge. Still, given the current study's unequivocal demonstration of the importance of the concept of perceptual load to our understanding of driving performance, such a model will have to include perceptual load at different regions of the scene as one of the factors affecting driving.

On a practical level, our findings suggest that future studies of driving safety, particularly, those that involve drivers' attention and distraction, would benefit from taking perceptual load into account. For instance, two preliminary studies suggest that the level of perceptual load modifies the impact of two safety-related factors: in-car warning system and advertising billboards. When perceptual load was low in all regions, the presence of a warning system actually increased collisions proportion with peripheral events, and billboards' influence was largest with low central load and high peripheral load (Marciano & Yeshurun, 2012a, 2012b). With both safety-related factors, the manipulation of load level at different regions afforded a more elaborated account of their effect, demonstrating the importance of the current paradigm. Hence, these findings suggest that driving safety–related variables might be better understood if studied in a similar experimental paradigm.

There are some limitations to this study. A study simulating real-life settings is less controlled than a laboratory study, which might introduce possible confounding variables (Caird, Willness, Steel, & Scialfa, 2008). For example, objects' average size, including critical objects,

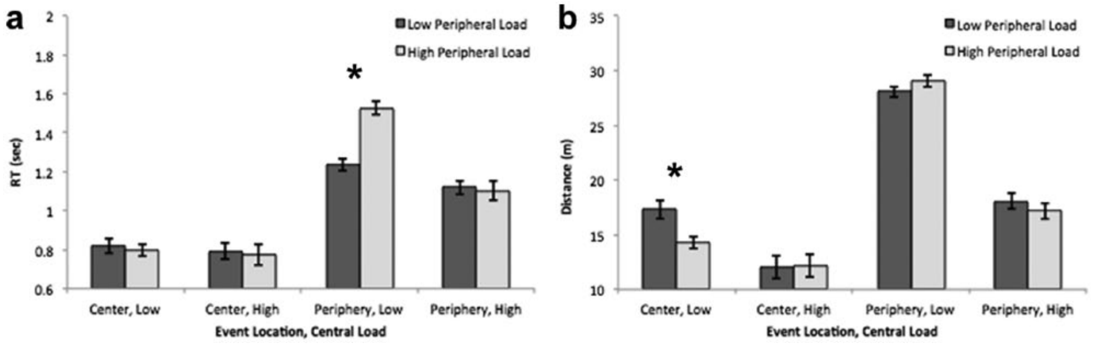

Figure 10. (a) Reaction time and (b) distance as a function of central load, peripheral load, and event location. The error bars reflect standard errors. An asterisk (*) denotes significant effect of the simple pairwise comparisons.

varied across the different regions (though both regions included large and small objects), and central information was more dynamic than peripheral information (though, again, both regions included dynamic and static objects). However, the aim of this study was to test the relevance of perceptual load under settings that are as realistic as possible, and these differences between central and peripheral regions are also present in real life. Besides, driving in a simulator is not equivalent to realistic driving (e.g., Blana, 1996; Mullen, Charlton, Devlin, & Bédard, 2011). Our scenarios, for instance, involved many critical events. This design might have caused our participants to be more attentive than in real-life driving. Critically, we used a within-subjects design, which might minimize the effect of this limitation. Another limitation is the lack of eye movement tracking. Still, since driving demands more resource allocation to the road than to its sides, one can assume that the participants most often fixated the center of the visual scene. Indeed, Harbluk, Noy, Trbovich, and Eizenman (2007) found that drivers gazed at the central region around 80% of their driving time, whereas less than 3% of the time was devoted to peripheral regions.

To summarize, the results show that the level of perceptual load has critical ramifications for driving behavior. Both the level of load on the road and the level of load on the sides of the road affected several measurements of driving performance, including driving speed, RT to critical events, collisions proportion, and the distance the car traveled from the onset of the critical event until response initiation. However, the pattern of load effect was somewhat different for central versus peripheral load. The former affected performance mainly via the tendency to adopt high driving speed with low level of load, whereas the latter increased the difficulty of the detection of critical events, particularly, those initiating from the sides of the road.

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KEY POINTS

- Both the level of load on the road and the level of load on the sides of the road affected driving performance.
- The pattern of load effect varied depending on the region at which the load was present.
- Load on the road mainly affected driving by encouraging the adoption of faster driving speed under low level of load.
- Load at the sides of the road mainly affected driving by impairing the detection of unexpected events, particularly, those initiating from the roadsides.

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