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# Effects of Verbal and Spatial–Imagery Tasks on Eye Fixations While Driving

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The consequences of performing verbal and spatial–imagery tasks on visual search when driving were studied. Twelve participants drove 84 km on 2 highways and 2 roads. On each route, they performed 2 verbal tasks and 2 spatial–imagery tasks while their eye movements were recorded. The same results were repeated on all routes. Pupillary dilation indicated similar effort for each task. Visual functional-field size decreased horizontally and vertically, particularly for spatial–imagery tasks. Compared with ordinary driving, fixations were longer during the spatial–imagery task. With regard to driving performance, glance frequency at mirrors and speedometer decreased during the spatial–imagery task. Results are interpreted in terms of multiple attention-resource theories; implications of internal distractions on road safety are discussed in terms of possible impairment in relevant information processing.

Most people often think about their everyday affairs and concerns while driving. What are the consequences of this mental activity on road safety? A high percentage of car accidents seem to be due to attention and information-processing failures rather than to lack of skills in performing responses (Shinar, 1978). Among other causes, errors in detecting relevant information can occur because of internal distraction: People change their visual search patterns or look but do not really see when they worry about personal problems or get involved in other mental tasks (Rumar, 1990). Visual perception is the main source of information when driving, and attention is crucial to visual perception. Information located in unattended places is scarcely processed or not processed at all (Johnston & Dark, 1986; Theeuwes, 1995), and attention plays an essential role in visual inspection strategy, especially in planning eye movements (Henderson, 1993) either toward locations preselected by expectations or toward objects that automatically attract attention because of conspicuous or contrasting attributes (Theeuwes, 1993, 1995).

This investigation focuses on the effects of mental tasks on visual search behavior while driving and assumes that eye movements reflect attentional states and changes. Eye movements are considered the behavioral interface between attention and information acquisition from the driver's environment. In the past century, Von Helmholtz (1962) pointed out the independence between attention and gaze. In fact, in laboratory research on covert attention, investigators have to discard eye movements so that they can infer that a process is really attentional (Van der Heijden, 1992). However, in ordinary activity, both attention and eye movements usually go together so that in a complex activity such as driving, it seems justified to interpret a change in visual inspection patterns as an indicator of a change in the assignment of spatial attention (Kahneman, 1973; Moray, 1990, 1993). According to Moray (1990, 1993), information acquisition while driving is limited by eye movement characteristics, and attentional changes in dynamic real environments are equivalent, in operative terms, to changes in eye fixations. Van der Heijden (1992, 1996) also supported the idea that capacity limitations in visual attention are due to constraints in the visual search system.

From a theoretical point of view, we considered divided attention limitations in the present study. Within this framework, we assume that resource limitations are specific in nature. Attention can be seen as a system to control human action. Its purpose is to distribute limited resources among various tasks (Kahneman, 1973), including the assessment of task difficulty and the assignment of resources according to priorities. Although Kahneman (1973) and, more recently, Cowan (1995) considered limited resources to be central and nonspecific, other researchers have posited the existence of limitations due to the specificity of attentional resources. Consequently, several tasks would only come into conflict when the same kinds of resources are required (Näätänen, 1992; Navon & Gopher, 1979; Wickens, 1984, 1992). Wickens (1984, 1992) introduced a taxonomy of specific resources, and, at the level of the central processes of encoding and perception, he argued that there is evidence that at least two types of resources exist: verbal and spatial or imagery resources. Considering the notoriously visual and spatial character of information acquisition while driving, we expected the ordinary visual search behavior to be more affected by performing concurrent tasks that require visual imagery or spatial resources than by performing verbal tasks. It is clearly established that mental image

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processing and visual perception share the same brain structures to a high degree (Farah, 1985; Kosslyn, 1988; Posner & Raichle, 1997). In addition to neurological structures, other processes may also be involved: According to Carpenter and Just (1978), ocular fixation patterns are involved in mental imagery rotation tasks, even when perceptual representations are recalled from memory. Therefore, if ocular inspection is required for visual information processing, then we can expect eye performance to be more affected by concurrent mental spatial–imagery tasks than by verbal tasks.

Research on cognitive processes and strategies based on eye movement analysis produced important results in very different contexts, such as reading (Rayner, 1998), visual search (Sanders & Donk, 1996), display sampling and monitoring (Senders, 1983), and scene and picture scanning (Rayner, 1998). In a comprehensive review of literature, Rayner (1978) suggested that it is difficult to generalize results from one particular task to another. The driving task involves specific characteristics, such as a dynamic environment and observer, a three-dimensional visual field, and, particularly, the relevance of behavior to survival (the existence of risk associated with processing relevant information). Consequently, specific research on visual search while driving has not had much opportunity to benefit from results obtained in other fields, particularly with regard to applied research goals.

In spite of the importance of attention and visual inspection in traffic, research on eye movements as a function of attentional workload while driving is scarce, especially if the type of attentional resources involved is taken into account. Not so long ago, this could be partially explained by the technical complexity of recording eye movements during driving in real traffic without causing great experimental interference with normal driving (Moray, 1990).

Several studies on eye movement while driving analyzed the effects of environmental variables that are interpreted in terms of attention: curve negotiation (Land & Horwood, 1996; Land & Lee, 1994; McDowell & Rockwell, 1978), expectancy at intersections (Theeuwes, 1996), lane effect (Hella, Neboit, & Laya, 1994), in-car devices and tasks (Reeves & Stevens, 1996; Summala, Nieminen, & Punto, 1996; Wikman, Nieminen, & Summala, 1998), road type (Crundall & Underwood, 1998; Wikman et al., 1998), and traffic complexity (Miura, 1986, 1990). Some individual differences were also interpreted in attentional terms, such as driving expertise (Crundall & Underwood, 1998; Crundall, Underwood, & Chapman, 1997; Mourant & Rockwell, 1972; Wikman et al., 1998) and familiarity with the route (Mourant, Rockwell, & Rackoff, 1969), with the assumption that expert drivers or those who are more familiar with the route use less processing resources. However, these differences in driving expertise and familiarity with route cannot be isolated from aptitudes and strategy learning, including visual scanning strategies (Summala et al., 1996). Some studies performed in simulated environments (Crundall et al., 1997; Huges & Cole, 1988; Theeuwes, 1996) could not guarantee that the attentional requirements were equivalent to real driving, especially as far as the perception of risk is concerned. In the case of environmental variables, changes in visual scanning behavior reflect the need to search for visual cues and objects, which leads to a time-sharing strategy (the eye cannot look at two locations at the same time).

Despite researchers' common subjective experience with the potential effects of internal dialogues and mental activity as a source of distraction, the study of attention while driving has neglected the relevance of mental activity itself, its potential interference with the driving task, its significance in terms of risk, and, eventually, the possible differences between different types of mental activities. Lack of literature on the effects of mental activity on visual search while driving makes it more difficult to make predictions about the expected effects. As far as possible, we attempted to advance some specific hypotheses; however, some results were not predictable, in spite of theory and literature. In particular, we considered the following aspects.

We considered pupillary dilation to be an indicator of attentional workload. Most of the researchers in the above-mentioned studies presumed that attentional workload differences were attributed to predefined environmental conditions. Although these assumptions seem well founded, there is no independent measure of attentional workload itself. In the present study, we used the pupil size as an appropriate variable for this purpose (Beatty, 1982; Hoecks & Levelt, 1993; Janisse, 1977; Kahneman, 1973). We expected to find pupillary dilation contingent on task performance, assuming that performing mental tasks implies an increment of attentional workload compared with ordinary driving. The comparison of pupil diameter between tasks should also allow us to evaluate whether the two tasks (verbal and spatial–imagery) were equivalent in attentional workload and, consequently, would help interpret the remaining results.

The fixation duration, or its approximate inverse, the fixation rate, is without doubt the most extensively used parameter in various studies, although its meaning is far from clear. In the above-mentioned research, a decrease in fixation duration was associated with a greater need for visual inspection because of greater scene complexity (Miura, 1986; Underwood & Radach, 1998). Kahneman (1973) also stated that eye movement rate often reflects the rate of thoughts, even if there is no spatial component, as in the case of mental tasks. However, it is well established that fixation duration increases with the amount of information to be extracted from a target (Rayner & Morris, 1990). However, neither these empirical results nor the early models relating fixation duration with information theory (Senders, 1983; Sheridan & Ferrel, 1974) encourage hypothesizing about the expected results when participants have to attend to driving demands while performing one of two kinds of mental tasks.

Previous research has established that high attentional workload produces attentional focus narrowing. In the above-mentioned studies, workload was contingent on the need of increased visual processing, and the focus narrowing was deduced from spatial variability reduction of fixations (Underwood & Radach, 1998) and peripheral processing impairment (Miura, 1986, 1990). If this narrowing effect is attentional, then it should also occur when the increment of attentional demands is due to concurrent cognitive tasks

instead of to an increase of visual scene complexity (which could imply specific visual search demands). Additionally, if eye movements in dynamic environments reflect the assignment of attentional resources to objects or locations, then this attentional narrowing should cause a reduction of the functional visual field, which could be relevant to road safety.

We performed the present research in real traffic. With regard to the above-mentioned investigations, some differential characteristics were introduced. First, we manipulated attentional demands more directly by asking the participants to perform a second mental task while driving. The second task, in principle, should not cause obvious structural interference; that is, it should not require the driver to look anywhere. Second, we varied the kind of mental task (verbal or spatial–imagery) on the hypothesis that the spatial–imagery task should produce more pronounced effects (or at least different ones) on ocular parameters than the verbal task: When driving, eye movements are used for spatial inspection and the manipulation of mental images shares the same resources as visual perception. Third, we repeated the experimental procedure on four different road scenarios, two highways and two roads, that had very different road designs and traffic conditions. The persistence of the results on different types of roads and traffic conditions allowed us to draw solid and generalizable conclusions. Fourth, for each condition (driving with no mental task, with verbal task, with spatial–imagery task), pupil size and six fixation parameters were analyzed: mean fixation duration, horizontal and vertical coordinates on the visual scene, and their respective variability across fixations. We also included a complementary analysis of saccadic size. Finally, in view of the important effects observed in the ocular parameters and their applied implications, we introduced an additional analysis of driving activity that focused on speed and glances at mirrors and dashboard.

## Method

### *Participants*

Twelve participants, 7 women and 5 men, ages 21 to 37 years old ($M$ = 26.25 years, $SD$ = 5.01) comprised the sample. All of them had more than 2 years of driving experience, and their total mileage was in the range of 15,000 to 300,000 km. None of them was familiar with the experimental route or the particular model of car used for the experiment (Citröen, BX-GTI, Madrid, Spain). They were paid for taking part in the experiment. The data of 2 participants in the road conditions were discarded because of a technical failure in the recording system; the final sample was composed of 12 participants for two highways and 10 participants for two roads.

### *Design, Instruments, and Procedure*

The experiment covered a total driven distance of 83.7 km: 43.1 km on two highways (Highway 1, 18.4 km; Highway 2, 24.7 km) and 40.6 km on ordinary roads (Road 1, 21.9 km; Road 2, 18.7 km). We obtained the data in four consecutive sessions of approximately 20 min each, with short interruptions to change the videotapes. The analyzed data correspond to a sample of various road and highway sections. Particular locations and situations, such as intersections, roundabouts, and highway entrances and exits, were excluded from the experimental conditions to eliminate noise due to possible artifacts attributed to those sites. All the roads and highways were selected near Madrid in the following sequence: Highway 1, Road 1, Highway 2, Road 2. On a 4-point scale that assessed traffic density, Highways 1 and 2 shared approximately the same density, whereas Road 2 had considerably more traffic than Road 1. As far as the course is concerned, Highway 1 was winding, with twice as many curves as Highway 2, whereas the Roads 1 and 2 were similar. All the sessions were performed between 10 a.m. and 2 p.m. and with normal daylight and dry weather conditions.

We used an instrumented car, a Citroën BX-GTI provided with an advanced head-free eye tracking system. The car computer simultaneously recorded mechanical parameters and videotape. The details of the complete system can be found in Nunes and Recarte (1997), and the details of the eye tracking system appear in Gottlieb, Scherbarth, and Guse (1996). We summarize only the main features of the system here. The instrumented car is equipped with different sensors to measure the dynamic state of the vehicle (speed, rotations per minute, three axis acceleration) and the human responses at the main vehicle controls (steering wheel, pedals, lights, turning signals). This information is recorded on a Versa Module Eurobus (VME) computer at a 50-Hz rate. The eye tracking system is a video-based system that allows unobtrusive eye movement recording. An amplified image of one of the driver's eyes (usually the right eye) is obtained by an infrared video camera installed on the dashboard. Two pulsating infrared sources installed on the dashboard produce two corneal reflexes that are used to calculate on-line eye gaze and to produce a data file. A second camera (the scene camera), fixed inside the car close to the driver's viewpoint, is used to produce a video output with a cursor superimposed on the road scene. A parallax correction algorithm compensates the distance between the driver's viewpoint and the scene camera. The driver's head is free of any device, which allows unobtrusive measurement with no visual field restrictions, contrary to other systems that use special goggles or helmets. All the eye measures are obtained on-line from the eye image. The system is able to track and search the eye automatically, within a range of motion that covers most common head movements while driving. An algorithm guarantees an automatic tracking routine that moves the eye camera according to the driver's head movement to keep the driver's eye within the field of the eye camera. An additional searching routine is also performed automatically when the eye is closed or the driver's head moves out of the measurement range. During these searching lapses, no data are obtained until the driver's eye is back within the measurement range. Normally, we obtained valid data 85% of the time, which is fairly acceptable, considering the advantage of head-movement freedom. The system output integrates both head and eye movement on-line, permitting the monitoring of visual performance during the session. The temporal resolution of the eye tracking system was 20 ms (sampling rate of 50 Hz), and the spatial resolution was within the range of 0.5° to 1.0°. A previous calibration routine was performed for each participant. The video output was recorded on a professional videotape recorder, provided with a longitudinal frame code, which was also recorded by the system to synchronize each video frame with the numerical data. This allowed precise qualitative analysis of the visual search behavior. The eye tracking system data and the mechanical parameters recorded on the VME computer from the car were also synchronized on-line.

After the calibration routine of the eye tracking system for each participant, the experimenter instructed the participant about the route to be followed and the tasks to be performed. Before the experimental route, participants drove for 25 km to become familiar with the car. Driving instructions emphasized that they

should drive as usual. Then the session began. When the session began, the experimenter, from the back seat, told the participant when to start or stop driving, as well as when he or she should start or stop performing an experimental task. After the driving session, participants answered a questionnaire with several items about the experiment. To have some general information about the degree of experimental interference in driving style as a whole, we asked participants to rate the similarity between their driving style during the experiment and their normal everyday driving style on a subjective scale of 100 points. The average similarity score was 75.

The 16 mental tasks were carried out in periods of 30 s each, during normal driving. There were two types of mental tasks—verbal or spatial–imagery—with eight alternatives for each type. The verbal tasks consisted of repeating words starting with a certain letter indicated by the experimenter for 30 s. A set of initial letters, with a similar number of entries in the dictionary, was selected. The spatial–imagery tasks consisted of image generation, sometimes including mental image rotation. We instructed participants to imagine the letters of the alphabet, one by one, from *A* to *Z*, and to say which letters fulfilled one of the following conditions: (a) which letters remained unchanged when rotated vertically, (b) which letters remained unaltered when rotated horizontally, (c) which letters were "closed," and (d) which letters were "open." The open or closed concept was explained using numbers as examples: *6* and *0* were defined as closed (they contain a closed area) and *3* and *5* were defined as open. These alternatives, combined with lower case or capital letters, produced a total of eight spatial–imagery tasks. Instructions and training were carried out before running the test, with digits 0 to 9 to exemplify the spatial–imagery tasks. On each route, two verbal and two spatial–imagery tasks were performed. A microphone was used to record the participant's responses. The task sequence was balanced among participants and routes so that all tasks were performed on all routes. The participants were not familiar with the route. At the beginning of each recording session, participants were informed about their destination so that they would look for it on the traffic signs. Therefore, the drivers had to keep the name of the destination active in their short-term memory while driving or performing any task.

The 50-Hz raw data for all the variables were reduced to other files in which the fixations were the unit of analysis. For each fixation, we calculated the corresponding statistics (usually the mean) of each variable, using all the samples belonging to that fixation. A *fixation* is defined as a sequence of consecutive samples of gaze coordinates located approximately in the same place, according to predefined temporal and spatial threshold criteria. For temporal criterion, taking into account that the sampling rate was 50 Hz, we decided there should be at least three samples (i.e., the minimum duration of a fixation should be 60 ms). For spatial threshold, we considered a value close to the spatial resolution of the measurement system, that is, approximately 1° visual angle. In operative terms, this criterion was translated to the internal units of the system, which are pixels on the video scene. Taking into account that the correspondence between angle size and pixels depends on the lens used in the scene camera, we calculated empirically that 5 pixels would be an acceptable criterion to establish this threshold. On the basis of these conditions and taking into account previous studies and algorithms (Jacobs, 1986; Karsh & Breitenbach, 1983; Mannan, Ruddock, & Wooding, 1995), we built an algorithm and custom-made software adapted to the peculiarities of the data-file structure of the eye tracking system. Because of the limitations of temporal resolution, no information was available to make a detailed analysis of saccade characteristics, such as latency or speed. Saccades are inferred as jumps between fixations, and their amplitude can be evaluated as the distance between fixations.

In summary, with regard to mental task performance, there were three experimental conditions: no task, verbal task, and spatial–imagery task. The fixation was the unit of analysis. An experimental design of 3 (tasks) × 2 (roads) was used separately for highways ($n$ = 12) and for roads ($n$ = 10), with repeated measures in all six conditions. For each type of route and task condition, we analyzed 12 dependent variables, and the measurements and interpretations are discussed below.

## Results

The analysis is based on 79,632 fixations that occurred in different conditions: 62,053 (77%) during ordinary driving (no task), 8,423 (11%) while driving with verbal task, and 6,661 (8%) while driving with spatial–imagery task. A small proportion of fixations, 2,495 (3%) occurred while the experimenter was instructing the participant when to start or stop performing one of the 16 specific task alternatives. With regard to the defined experimental conditions, these short periods of time were excluded from the analysis.

First, we present the analysis of oculomotor parameters (pupillary dilation, mean fixation duration and its variability across fixations, mean horizontal location and its variability, mean vertical location and its variability, and horizontal and vertical saccadic size). Second, we present driving parameters, such as vehicle speed and glances at mirrors and dashboard. To analyze ocular parameters and speed for each variable, we used a 3 (task conditions) × 2 (routes) repeated measures analysis of variance (ANOVA) for the highways ($n$ = 12) and for the roads ($n$ = 10). Besides the test of global significance, we carried out the Helmert repeated measures contrast, which provides a comparison between performing and not performing a task as well as between verbal and spatial–imagery tasks (Norusis, 1993). The analysis of the variability of fixation duration and of gaze direction (horizontal or vertical variability of spatial fixation coordinates) does not refer to the variability among the participants but rather to the variability in the participant's fixations in each condition. For this purpose, an individual variability score was defined as the standard deviation of each participant in each condition. Although the direct units provided by the eye tracking system are pixels, these units were converted into degrees of visual angle to make the expressed values of fixation coordinates and spatial variability more comprehensible. The coordinates ($X$ = 0, $Y$ = 0) correspond to a gaze direction defined by a longitudinal axis passing through the driver's eye when he or she looks straight ahead in the same direction as the car trajectory. In dynamic terms, this point corresponds to the location of the focus of expansion. Because the coordinates of this point depend on the driver's height and his or her position in the vehicle, we established a calibration routine to calculate it empirically for each participant. The eye tracking system is designed to compensate for parallax error due to the distance between the scene camera and the driver's eye and it updates the gaze data, compensating for head movements. Therefore, participants' gaze direction data are comparable in subjective terms of looking upward, downward, left, or right, and not only at externally predefined locations or areas.

### *Ocular Parameters by Task*

In Figures 1 to 7, the results of the five ocular variables are displayed: pupil diameter, fixation duration, and their hori-

zontal and vertical coordinates in the visual field. The variability across fixations of the last three for each condition are also shown. The analyses were performed separately for highways and roads.

*Pupil diameter by task.* First, we analyzed the pupil diameter. To allow for the interpretation of pupillary dilation as a reliable indicator of attentional resource demands, we discarded illumination changes as an alternative explanation. Because it was impossible to control the environmental luminance experimentally, we compared pupil diameter during task performance and during ordinary driving: four samples of pupil size for 30 s in task conditions were compared with pupil size measured at intervals between tasks (no task condition) along the same route. The results showed systematic differences that were consistently observed on all four routes, despite variations in the sun's orientation along the routes. Because it is extremely unlikely that the luminance changed systematically according to task performance, it seems justified to attribute pupil diameter variations to an increase of attentional demands due to task performance. Figure 1 displays the pupil diameter data.

The ANOVA of highway data indicated significant differences in pupil diameter by highway, $F(1, 11) = 18.09$, $p < .01$, related to the predominant sun orientation. However, the task effect was even greater than that of the possible differential illumination of the highway, $F(2, 22) = 27.28$, $p < .001$. This effect was significant when comparing task with no task, $F(1, 11) = 47.18$, $p < .001$, but not when comparing verbal with spatial–imagery tasks, $F(1, 11) = 3.27$, $p > .05$. No interaction was found between highway and task. On the road, there was no significant difference in pupil diameter by road. The task effect was again significant, $F(2, 18) = 13.84$, $p < .001$, and, as on the highways, this only occurred when comparing task with no task, $F(1, 9) = 36.39$, $p < .001$, but not when comparing verbal and spatial–imagery tasks, $F(1, 9) < 1$, $p > .05$. No interaction was found between road and task.

The difference between highways was trivial from the research viewpoint: On Highway 2, pupil diameter was smaller than on Highway 1 because of the predominant sun orientation. With regard to differences between tasks, although the participants' pupil size was systematically bigger during the spatial–imagery task than during the verbal task, the differences were not statistically significant. Therefore, we can assume that both tasks consume approximately the same amount of attentional resources, so that if differential effects between them are obtained in subsequent analyses, then these effects should not be attributed to differences in the amount of resource consumption but rather to the specific type of processing resources required. Considering the questionnaire data about the subjectively reported task difficulty, we found that all but 1 of the participants regarded the verbal task as more difficult and causing more interference with driving than the spatial–imagery task. Taking into account both the questionnaire and the pupil size data, one would conclude that if the effects of tasks on eye movements are due to differences in attentional workload, then the expected differences between tasks should be equivalent or larger in verbal tasks. Nevertheless, the largest effects were produced by the spatial–imagery task.

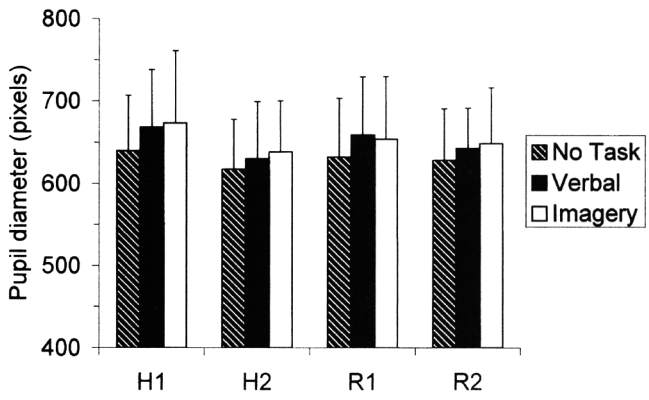


*Figure 1.* Mean and standard deviation (error bars) of pupil diameter (in pixels) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

In summary, performing mental tasks while driving caused an increased attentional workload on ordinary thought, as shown by pupillary dilation. The attentional workload was approximately the same for both kinds of tasks; this effect was more conspicuous, taking into account that it was verified despite daylight variations or other sources that could increase the variability of this measure.

*Fixation duration by task.* The results on mean fixation duration can be seen in Figure 2. The ANOVA showed a small but significant effect of highway, $F(1, 11) = 6.42$, $p < .05$. On Highway 2, eye fixations were about 30 ms shorter than on Highway 1. We found no convincing explanation for this because the course of the route, the driving speed, the traffic conditions, and the familiarity with the test could not explain this and other differences between the routes. The effect of task on the mean fixation duration was significant, $F(2, 22) = 6.60$, $p < .01$. However, this effect was not due to merely performing a task while driving but to the type of task: The difference between task and no task was not significant, $F(1, 11) = 0.33$, $p > .05$, although this can easily be explained by the opposite effects of verbal and spatial–imagery tasks when considered together. There were significant differences between tasks, $F(1, 11) = 11.49$, $p < .01$. As can be seen in Figure 2, performing a verbal task produced shorter fixations than driving with no task, although this difference was not significant, whereas performing a spatial–imagery task produced longer fixations than driving with no task or with verbal tasks. The interaction between highway and task was not significant.

The ANOVA by roads also revealed a significant effect of road, $F(1, 9) = 7.4$, $p < .05$. Eye fixations were systematically shorter on Road 2 than on Road 1. Here again, we have no convincing explanation for this difference. The effect of task on the mean fixation duration was significant, $F(2, 18) = 9.57$, $p < .01$. As on highways, this effect was not due to merely performing a task while driving normally but to the type of task: The difference between performing and not performing a task was not significant, $F(1, 9) = 1.49$, $p > .05$, but there were significant differences between the tasks themselves in opposite directions with regard to

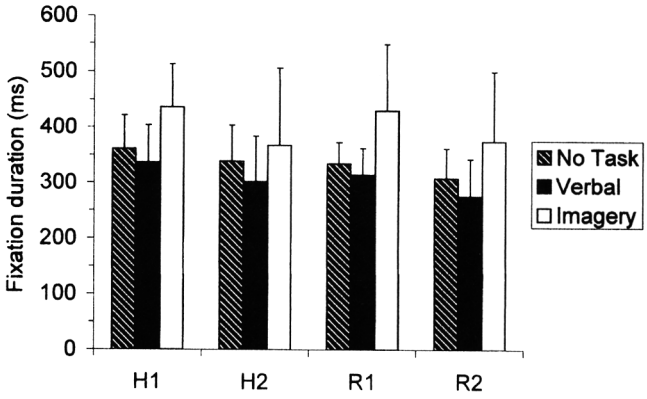


*Figure 2.* Mean and standard deviation (error bars) of fixation duration (in milliseconds) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

ordinary driving, $F(1, 9) = 17.00$, $p < .01$. The interaction between road and task was not significant.

In summary, fixation duration increased when participants performed a spatial–imagery task. This remained constant across the four routes, in spite of the existence of differences between routes in fixation duration.

*Variability of fixation duration.* There are two hypothetical alternatives to explain the increment in mean fixation duration associated with spatial–imagery task: Either most of the fixations increased systematically (increase in mean value but not in variability across fixations) or some very long fixations occurred, although most fixations were of ordinary duration (increase in variability across fixations as well as in the mean duration). The data of this variability, shown in Figure 3, clearly reflect the latter case because the values are practically analogous to those of the mean duration.

To analyze this variable, we used the values of the standard deviation of fixation duration within each condition and participant. The ANOVA of duration variability as a function of highway indicated that this variable had no effect, although there were differences in the mean duration. Task had a general significant effect, $F(2, 22) = 9.03$, $p < .01$: The difference between verbal and spatial–imagery tasks was statistically significant, $F(1, 11) = 13.85$, $p < .01$, but no significant difference was found between task and no task. The interaction between task and highway was not significant. The roads had an effect on variability of fixation duration, similar to their effect on mean duration, $F(1, 9) = 5.41$, $p < .05$. The effect of task on the variability of fixation duration was, again, significant and analogous to that observed in the mean duration, $F(2, 18) = 10.35$, $p < .01$. Whereas the effect between task and no task was not significant, $F(1, 9) = 0.49$, $p > .05$, there was a significant effect between verbal and spatial–imagery task, $F(1, 9) = 19.85$, $p < .01$. The interaction between task and road was not significant.

In summary, for fixation duration, an identical pattern was produced on highways and on roads: Performing a mental spatial–imagery task produced longer fixations than a verbal task or than ordinary driving. This increment in fixation duration can be described as an eye freezing effect: When performing a spatial–imagery task, the eye often freezes, producing long fixations mixed with others of normal duration as observed in the variability increment. These results may have theoretical implications, because the observed effects do not seem to depend on external events, from which more or less information must be extracted, but rather on mental processes. This lends weight to the idea that the workload itself does not produce a unique effect on fixation duration, but rather different effects, depending on the type of mental task performed.

*Horizontal gaze direction.* The results of the mean horizontal fixation coordinate can be seen in Figure 4. The ANOVA revealed no significant differences for either highway, task, or for the Highway × Task interaction. The same pattern persisted on the roads as on the highways: absence of significant effects regarding the horizontal position of fixations, as a function of road. No significant differences were found for task or for the Road × Task interaction. Consequently, the mean horizontal gaze direction was not affected by mental task performance.

*Horizontal variability of gaze direction.* The results regarding the horizontal variability of fixations are displayed in Figure 5. The standard deviation for each condition and participant was used for this analysis. The ANOVA of the highway data revealed no significant differences for highway. However, there were clear differences associated with task, $F(2, 22) = 16.62$, $p < .001$; these differences were significant when comparing ordinary driving with task conditions, $F(1, 11) = 16.73$, $p < .001$, and also when comparing verbal with spatial–imagery task, $F(1, 11) = 15.93$, $p < .001$. These differences, which can be attributed to task performance and type of task, remained unaltered on both highways because the interaction was not significant. The ANOVA of the two roads revealed significant differences as a function of road, $F(1, 9) = 17.41$, $p < .01$. The variability was greater on Road 2 than on Road 1. There were also clear differences associated with task, $F(2, 18) = 14.86$, $p < .001$, which were significant when comparing ordinary driving with task conditions, $F(1, 9) = 23.98$, $p <$

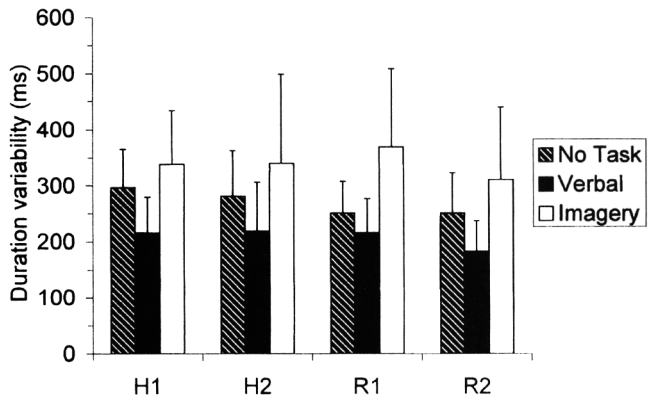


*Figure 3.* Mean and standard deviation (error bars) of variability of fixation duration (in milliseconds) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

.01, and also when comparing verbal and spatial–imagery tasks, $F(1, 9) = 8.99, p < .05$. The interaction between road and task was not significant. However, in post hoc comparisons, the Helmert contrast revealed a small, but significant, effect between road and task–no task, $F(1, 9) = 7.15, p < .05$, indicating that the difference was greater on Road 1.

In summary, when a mental task is performed, the mean horizontal gaze direction remained unaltered. We found no reason to expect any effects. An important decrement in the horizontal variability of fixations was observed, which was more marked for mental spatial–imagery than for verbal tasks (see Figure 5). The systematic verification of these results on both the highways and the roads, with no additional interactions, lends weight to their relevance.

*Vertical gaze direction.* Drivers usually drive looking slightly below the focus of expansion. When mental tasks are performed, vertical gaze direction rises between 0.5° and 1° (see Figure 4). The ANOVA of the mean vertical position showed a significant, but small, effect of highway, $F(1, 11) = 6.03, p < .05$. The gaze direction was approximately 0.5° lower for Highway 2 than for Highway 1. On Highway 1, the participants had to explore more often various indicator panels, which were mounted over the highway. The task effect was more pronounced, $F(2, 22) = 9.51, p < .01$, indicating that when a mental task was performed, the gaze direction rose. This effect was significant when comparing ordinary driving with driving while performing a task, $F(1, 11) = 12.06, p < .01$, but not when comparing the tasks themselves, $F(1, 11) = 0.17, p > .05$. There was no interaction between highway and task.

The ANOVA of vertical gaze direction on roads showed a significant, but small, effect of road, $F(1, 9) = 6.90, p < .05$. The mean vertical gaze direction was slightly lower for Road 2 than for Road 1, possibly because of a higher frequency of gazing right ahead of the vehicle because of higher traffic density. The effect of task was significant, $F(2, 18) = 3.68, p < .05$, showing that the gaze rose when performing a mental task. This effect was significant when comparing ordinary driving with task performance, $F(1, 9) = 8.63, p < .05$, but not when comparing tasks. There was no interaction between road and task. The effect of gaze raising observed on the highways also occurred on both roads.

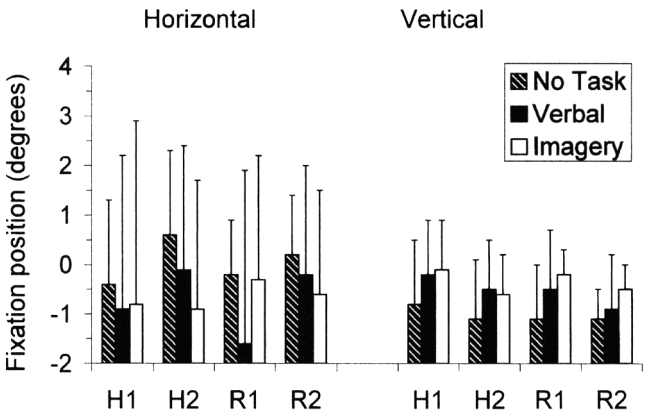


*Figure 4.* Mean and standard deviation (error bars) of horizontal and vertical fixation position (in degrees) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

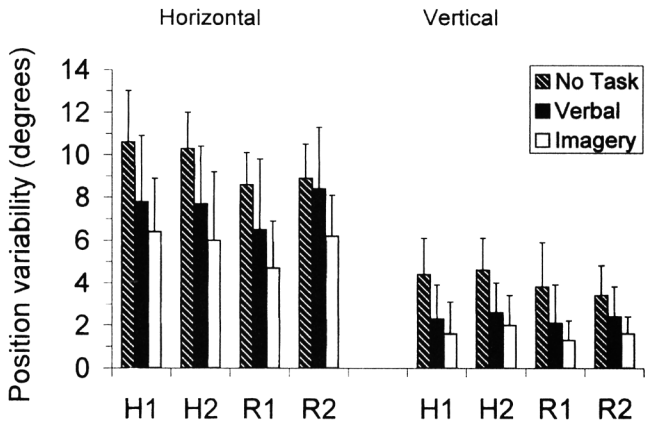


*Figure 5.* Mean and standard deviation (error bars) of horizontal and vertical variability of fixations position (in degrees) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

*Vertical variability of fixations.* In the analysis of the vertical gaze variability, there were no significant effects of highway. When a task was performed, the effect was highly significant, $F(2, 22) = 71.11, p < .001$; when ordinary driving was compared with task performance, $F(1, 11) = 89.97, p < .001$, or verbal with spatial–imagery tasks, $F(1, 11) = 15.61, p < .01$. No interaction was found between highway and task.

On the roads, there were no significant effects of road. The effect of task was significant, $F(2, 18) = 24.53, p < .001$, both when comparing no task with task, $F(1, 9) = 39.47, p < .001$, and verbal with spatial–imagery tasks, $F(1, 9) = 7.11, p < .05$. There was no interaction between road and task. Thus, the results were identical to those obtained on the highways.

Figure 5 shows the pronounced drops in vertical gaze direction variability when ordinary driving was compared with task conditions and when verbal tasks were compared with spatial–imagery tasks. The homogeneity of these effects on both highways and roads can be seen. This reduction of the vertical amplitude of the visual inspection window was even more pronounced than that observed on the horizontal axis.

Considering both the horizontal and vertical axes, we found the spatial reduction of gaze variability to be the most important result of this experiment, especially regarding its implications for driving because of the important reduction of the visual inspection window. For the verbal task, we observed a reduction of 25% horizontally and 40% vertically, whereas for the spatial–imagery task, the reduction was of 40% on the horizontal and 60% on the vertical axis. The proportion of the relative sizes of the visual inspection window can be seen in Figure 6, each one corresponding to the data of a route. The dimensions of each rectangle are proportional to the standard deviations across the fixations previously displayed on the horizontal and vertical axes (see Figure 5).

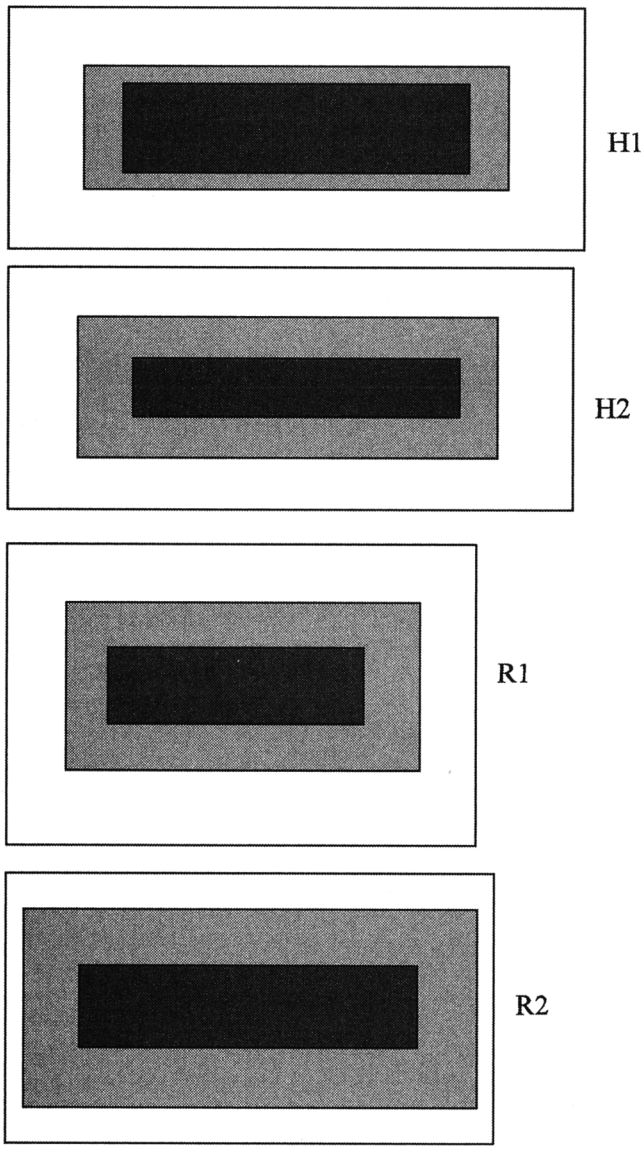


*Figure 6.* Visual inspection windows with no task (white), with verbal task (light gray), and with imagery task (dark gray). H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

*Saccadic size.* The reduction effect of the visual inspection window during tasks provides information about the spatial distribution of fixations but not about the oculomotor activity itself. One could speculate that the concentration of fixations around the focus of expansion should be accompanied by a saccadic size reduction. However, an increment of saccadic size is also compatible with the reduction of the visual inspection window through a different search pattern.

Although the temporal resolution of the eye tracking system did not allow a detailed analysis of saccades, it is possible to infer the saccadic size by calculating the distance between consecutive fixations. To perform this analysis, we considered some aspects of the eye tracking system to eliminate artifacts. When the system loses the participant's eye, usually because of a broad head movement, a search routine is automatically performed until the eye is found. In these cases, there is a time lapse between the last fixation detected before the eye was lost and the first fixation detected after the search routine. To eliminate this noise, we empirically established a threshold of 120 ms: Lapses higher than this threshold were eliminated, as they corresponded to blank data. We estimated that the highest expected saccadic size would be around 50°. Given that the mean saccadic velocity is around 1° every 2 ms (Fuchs, 1976), 100 ms are needed to perform a saccade of 50°. Findlay (1992) also estimated that a short saccade lasts about 20 ms, whereas a very long one lasts about 100 ms. The use of a threshold of 120 ms reduces the risk of eliminating real data.

As can be observed in Figure 7, the performance of a verbal task did not affect horizontal saccadic size when compared with ordinary driving. There were, however, marked effects in horizontal saccadic size associated with spatial–imagery tasks: $F(2, 22) = 7.33$, $p < .01$ on highways, and $F(2, 18) = 20.48$, $p < .001$ on roads. On the vertical axis (see Figure 7), there was a different pattern. Besides general differences between task and ordinary driving, $F(2, 22) = 24.75$, $p < .001$ on highways, and $F(2, 18) = 16.17$, $p < .001$ on roads, there was an effect associated with verbal task and another, more marked one, associated with spatial–imagery task.

### *Driving Variables*

The above-mentioned experimental results raise theoretical and applied issues, which are addressed in the General Discussion. In practical terms of driving, a significant functional consequence of the visual inspection window reduction could be the alteration of the inspection patterns of mirrors and speedometer, which have locations in the visual field fairly far from the central area, where most fixations occur. Possibly, a greater consumption of attentional resources because of the performance of a concurrent task, made drivers reduce their speed. Assuming that higher speed is more demanding, drivers could eventually reduce their driving speed to compensate for increased attentional de-

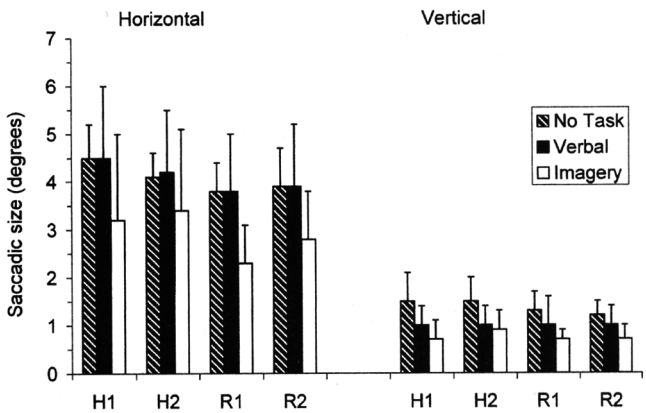


*Figure 7.* Mean and standard deviation (error bars) of horizontal and vertical saccadic size (in degrees) as a function of task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

mands because of task performance. However, ordinary driving is not usually extremely demanding, and drivers may have spare capacity to perform concurrent tasks without any speed alteration. Visual scanning changes may constitute an adaptive strategy to optimize visual processing and cope with the demands of both tasks simultaneously. These aspects are discussed below.

*Speed by task.* The ANOVA of the highways revealed significant differences as a function of highway, $F(1, 11) = 51.29$, $p < .001$. On Highway 2, speed was 11 kph greater than on Highway 1, probably because of its course (Highway 1 was more winding than Highway 2) and because of the participants' familiarity with the vehicle and the experimental situation (on Highway 2, they had already driven over 50 km, whereas on Highway 1, they had only had a previous adaptive period of 25 km). The effect of task and the interaction between highway and task were not significant. The ANOVA of road data revealed significant differences as a function of road, $F(1, 9) = 20.65$, $p < .01$. In this case, participants drove slower on Road 2 than on Road 1. The most plausible explanation is that traffic density was higher on Road 2. Neither the effect of task nor the interaction between road and task was significant, although participants clearly drove faster when performing both tasks than with no task, $F(2, 18) = 2.15$, $p > .05$. In fact, in the post hoc comparisons, the Helmert contrast revealed significant differences between task and no task, $F(1, 9) = 25.61$, $p < .01$. We speculatively suggest that driving on a road imposes more speed restrictions than does driving on a highway, and, therefore, more effort is needed to control speed. Carrying out these mental tasks reduces available attentional resources, which, in turn, decreases control (including glances at the speedometer, as discussed below), and in this case, results in increase of speed. Although a direct relation between speed and effort is usually presumed, the generalization of our hypothesis indicates the existence of an optimal speed that corresponds to minimum resource expenditure. Deliberate variation of this speed (to higher speeds but also to lower ones) requires attention to control it; this control diminishes if attention is directed toward other goals. To summarize, the performance of a mental task, either verbal or spatial–imagery, did not reduce vehicle driving speed, either on highways or on roads, at least within the speed range of the participants in this experiment.

*Glances at mirrors and speedometer by task.* The proportions of fixations on the interior mirror, the offside mirror, and the dashboard during ordinary driving and while performing verbal or spatial–imagery tasks are displayed in Figure 8. The percentages, with reference to the total number of fixations in each condition, revealed a very irregular distribution. Consequently, the distributions did not fulfill the normality assumption required for the analysis of variance. Therefore, we used the nonparametric Friedman test for repeated measures to analyze the significance of the differences.

Before describing the effects of task performance, we wish to point out some general data about mirrors and dashboard inspection. The dashboard is fixated almost twice as often as the left mirror, and the latter more than twice as often as the interior mirror, although there were large differences between the mirrors, depending on the route. When driving on highways, the interior mirror was looked at 10 times more frequently, and the left mirror was looked at more than twice as often, as when on conventional roads. There is no doubt that this was due to overtaking maneuvers on highways, which were practically nonexistent on roads. Glances at the dashboard, mainly at the speedometer, were

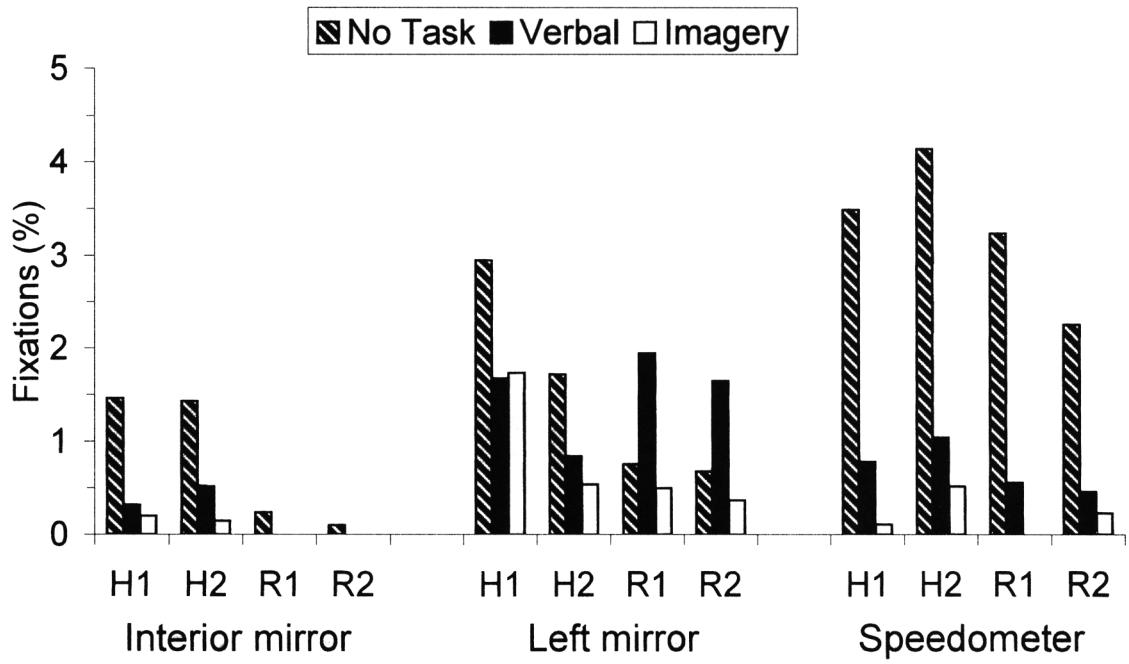


*Figure 8.* Percentage of fixations on interior mirror, left mirror, and speedometer, by task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

not affected by the type of road. As far as the fixation parameters on these objects are concerned, we want to emphasize the extreme nature of the horizontal and vertical coordinates with regard to the focus of expansion; the interior mirror was located, on the horizontal axis, between 40° and 45° to the right, the external mirror was located between 36° and 38° to the left, and the dashboard and the speedometer were located between 19° and 20° below the focus of expansion. It is important to bear this in mind because it may influence the total variability, as we see below. An additional aspect is that the fixations on these objects were, on the average, more than 100 ms shorter than ordinary fixations.

*Glances at the interior mirror.* Figure 8 shows that when driving normally, approximately 14 out of 1,000 eye fixations were directed at the interior mirror, and this number was basically the same on both highways. This number decreased to 4 out of 1,000 fixations when performing verbal task, and to 2 out of 1,000 (seven times less) for the spatial–imagery task.

The Friedman test revealed significant effects of the task on Highway 1, $\chi^2(2, N = 12) = 19.16$, $p < .001$. On Highway 2, the results were similar, $\chi^2(2, N = 12) = 17.90$, $p < .001$. Therefore, one of the effects of performing mental tasks on highways was a decrement of glance frequency at the interior mirror, to the same extent for both kinds of tasks. The interior mirror was glanced at less frequently on roads than on highways, where its function is clearer, especially for overtaking: Among all the participants and on both the roads, participants only glanced at the interior mirror on 47 occasions, always when they were not performing a task. Therefore, the percentages for the tasks are zero, as shown in Figure 8. The nonparametric Friedman test revealed significant effects on both roads, $\chi^2(2, N = 10) = 14.00, p < .001$, on Road 1 and $\chi^2(2, N = 10) = 10.00, p < .01$, on Road 2.

*Glances at the offside mirror.* The nonparametric Friedman test for the data of Highway 1 revealed significant effects of task, $\chi^2(2, N = 12) = 7.80, p < .05$. On Highway 2, $\chi^2(2, N = 12) = 5.60$, which is near the significance criterion ($p = .06$). On both roads, the results were significant: On Road 1, $\chi^2(2, N = 10) = 10.41, p < .01$, and on Road 2, $\chi^2(2, N = 10) = 4.10, p < .05$. The data of Figure 8 seem to imply that when performing a verbal task on the roads, participants looked at the left mirror more often than when either not performing a task or when performing a spatial–imagery task. However, as expected, they looked at the mirror more often in the no task condition than when performing a verbal task and more often when performing a verbal task than a spatial–imagery task. This apparent contradiction can be explained because only 1 participant performed most of the glances. In the nonparametric test, this is not taken into account because the test operates on the principle that only 1 participant out of 10 glanced at the mirror more often during the verbal task than when not performing a task. In summary, the frequency of visual inspection of the offside mirror decreased when a mental task was performed, on the highways as well as on the roads.

*Glances at the speedometer.* The results of the inspection of the vehicle's instruments on the dashboard (most of them at the speedometer) are especially clear, as far as the task effect is concerned. The percentage of fixations on the dashboard is relatively high and similar on both highways: About 4% of the total number of fixations were performed during ordinary driving, and this percentage decreased to less than 1% when a verbal task was performed, and to less than 1% when the mental spatial–imagery task was performed.

The nonparametric Friedman test revealed significant effects of task on both Highway 1, $\chi^2(2, N = 12) = 20.67$, $p < .001$, and Highway 2, $\chi^2(2, N = 12) = 21.51, p < .001$. On the roads, a similar pattern was found, although with lower percentages: About 3% of the fixations corresponded to normal driving. This percentage decreased to 1% with verbal task and to less than 1% with spatial–imagery task. The nonparametric Friedman test with repeated measures for the task revealed that on Road 1, all participants, without exception, observed the dashboard more often in the no task condition, $\chi^2(2, N = 10) = 18.73, p < .001$. Also, on Road 2, the effects of task were significant, $\chi^2(2, N = 10) = 14.35$, $p < .001$.

To summarize, we found that when mental tasks were performed, the percentage of glances at these objects, especially the speedometer, decreased sharply on all the analyzed routes. Regarding the type of task involved, the difference did not reach a clear significance level, so that, lacking additional evidence, we concluded that the effect was the same for both kinds of task.

From a theoretical perspective, these changes show that when attentional resources required for processing several information sources at once become scarce, the expected strategy is to disregard the less relevant sources. In fact, the speedometer showed the most pronounced effects due to task performance because, generally speaking, the information it provides is not as relevant for safe driving as that provided by the rear view mirrors.

## *Experimental Controls*

The above results were obtained in real traffic and, therefore, lack the controls that are normally applied in a laboratory. Because of this, one could speculate whether the results, partially or as a whole, could be due to a systematic error source associated with the task conditions (e.g., that the tasks were performed when driving slowly or with no traffic, and so forth). In this section, we review several possible variables that could offer alternative explanations to the above-described effects.

*Speed.* With regard to the differences between experimental conditions, the data suggest that speed did not affect the ocular inspection patterns because (a) there were no speed differences associated with performing the mental tasks, and (b) although there was speed difference between the two highways, the observed effects of task on the eye movements were similar on both, as already described. The same is valid for the roads.

*Traffic conditions.* With respect to traffic density on the different routes and in the three task conditions, we analyzed the traffic complexity. There were no significant differences associated with tasks. Therefore, we can discard traffic

density as an alternative explanation for the differential effects of the tasks.

*Time-lapses with no ocular data.* We have pointed out a narrowing effect of the visual inspection window, which was more pronounced during spatial–imagery tasks than during verbal tasks. Some of these differences may be biased because during the tasks (or some of them), more ocular data were missing because of a higher proportion of glances at extremely peripheral locations of the road scene, far from the available measurement range of the eye tracking system. In this case, if the spatial variability of fixations had been recorded, they would have increased greatly. To test this possibility, we analyzed the time lapses with blank data as a function of task conditions. On the basis of the criteria previously explained, Figure 9 displays the data on time lapse with no eye data (over 120 ms). The data clearly indicate that the participants glanced at locations outside the measurement range more frequently when performing verbal tasks than spatial–imagery tasks. Therefore, the true variability of fixations when performing a verbal task is, in fact, higher than the data we obtained, in which case, the differences between verbal and spatial–imagery tasks should be even more marked, whereas the differences between verbal task and normal driving should decrease.

*Glances at mirrors and at dashboard and fixation variability.* The decrement of glance frequency at mirrors and dashboard when performing a mental task poses a new problem, both technical and theoretical: Is this effect the consequence of the visual inspection window reduction or is it the cause of the narrowing effect? Statistically, it is a circular problem: The mirrors and the speedometer are located at the periphery of the driver's visual scenario. Therefore, glances in their direction greatly increase spatial variability. If the participants do not look at them, this variability decreases. However, from a psychological point of view, the issue is theoretically relevant. Is there a primary event of visual inspection window narrowing, or is it simply the consequence of not looking at the mirrors? Or, from an operative viewpoint, if we eliminate all the data in which the participants look at the mirrors and dashboard and reanalyze the spatial variability of fixations, will the narrowing effect still occur? We carried out these analyses for the variables that could be affected by these glances—the variability on both horizontal and vertical axes and the fixation duration (the latter because the fixations on mirrors and the dashboard were shorter). The results revealed that when the fixations on mirrors and speedometer were eliminated, all the previously mentioned effects persist, although logically somewhat attenuated. It seems clear that the narrowing of the visual inspection is, in itself, an important phenomenon, resulting from changes in attentional processes and not a mere consequence of the reduction of glance frequency at mirrors and speedometer. Instead, this glance reduction could be a consequence of these changes.

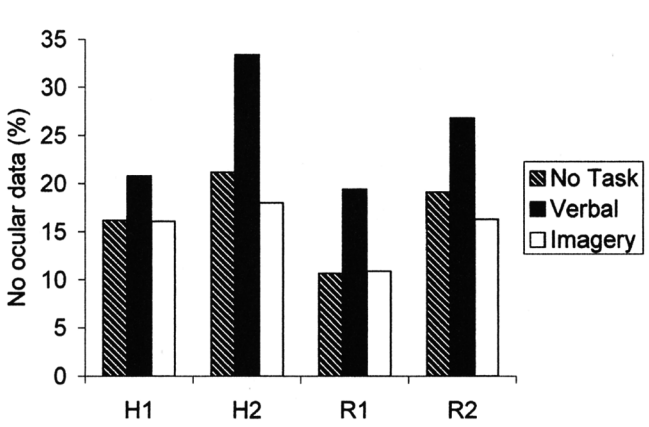


*Figure 9.* Percentage of time elapsed with no ocular data by task and route. H1 = Highway 1; H2 = Highway 2; R1 = Road 1; R2 = Road 2.

In summary: Both speed and traffic complexity can be discarded as alternative explanations of task effects. With regard to visual functional-field reduction, the higher percentage of blank data while a verbal task is performed suggests an even higher difference between tasks and raises a question about the differences between verbal task and ordinary driving. Finally, the visual inspection window reduction is more than just a statistical consequence of the reduction of glance frequency at mirrors and dashboard, as this effect also persisted when those devices were not looked at. Therefore, the reduction of the functional window can be considered an indicator of the reduction of the attentional focus, which caused the decrement of mirror and speedometer inspection.

## Discussion

We have shown that mental tasks imposed by the experimenter while the participant was driving, and, therefore, of a more mandatory nature than ordinary thoughts, produced (a) marked changes in the visual inspection patterns; (b) qualitatively different changes, depending on the type of processing resources required by the mental tasks; (c) the same effects in the four different driving scenarios; and (d) changes in practical driving behaviors, such as inspection reduction of mirrors and speedometer. Spatial–imagery tasks produced more marked effects in almost all the analyzed variables than verbal tasks. The effects observed while performing spatial–imagery tasks were as follows. First, we found an increment in mean fixation duration due to some long fixations and possibly associated with mental image inspection as part of the mental activity of image searching or rotating, as described by Carpenter and Just (1978). We suggest that these eye freezing responses produce impairment of environment perception. The pattern of alternating these long fixations with normal-duration fixations could be interpreted in terms of the sampling theory (Senders, Kristofferson, Levison, Dietrich, & Ward, 1967), as a means to reduce the cumulated uncertainty about the state of the moving scenario. Second, we found a marked reduction of the visual inspection window, both horizontally and vertically, possibly associated with narrowing of the attentional focus size. We also found smaller saccadic size and marked reduction of glance frequency at mirrors and speedometer. During verbal task, the visual inspection window was reduced compared with ordinary driving, although this effect may have been overemphasized because of the higher

proportion of blank data, and horizontal saccadic size was not altered, so that a different search pattern may be inferred.

From the outlook of attention, it seems that the specific nature of the resource limitations emerges, as opposed to the mere competition for general purpose resources (Wickens, 1984, 1992). Mental tasks requiring operations with images produce more pronounced and different alterations in the visual search behavior than those corresponding to verbal tasks, and this is not due to differences in the amount of effort required for each task. However, we assume the limitations of an applied experiment in a natural environment to verify the multiple resources hypothesis. Theoretically, one can always argue that the limitations are central and that central attention can be directed toward different structures in memory or toward different processing subsystems (Cowan, 1995) and that, in short, the issue is about structural interference between areas related to eye movements and areas involved in performing the tasks. In any case, an explanation in terms of input or response modality can be discarded because in both tasks, the input and the response were verbal.

With regard to the implications for driving, the spatial reduction of the visual inspection window, including the reduction of the inspection of mirrors, could be interpreted as a predictor of decreased probability of detecting traffic events, particularly when performing mental spatial–imagery tasks. However, considering the limitations of interpreting eye movements in terms of attention, this cannot simply be assumed. The issue of whether the narrowing of the visual inspection window causes loss of peripheral visual capacity and visual information processing (peripheral or otherwise) remains open. Practically speaking, such visual concentration may be no worse than driving with disperse attention and gaze (landscape, vehicles, houses, etc.). A more direct demonstration, similar to Miura's (1986, 1990) discussions, is necessary to discover whether events occurring in the visual periphery while driving are more poorly detected when performing a mental task or whether information (peripheral or otherwise) is more poorly processed when performing a task. On the one hand, any reduction of information availability can be interpreted as a higher risk level. On the other hand, this is only true if, while driving normally, all our attentional resources are focused on relevant driving information so that any reduction in visual processing would imply less availability of this information. Do all fixations on the road represent relevant information processing? While looking at the road scenario, there is a lot of information that is irrelevant in a specific driving context or situation. When observing a reduction of the inspection of speedometer or mirrors or of the functional visual field, we do not know whether the eliminated glances correspond to relevant or irrelevant information, as far as road safety and optimization of the driving strategy are concerned.

From a practical point of view, this experiment raises several issues about its applied potential. How similar are people's everyday mental activities (listening to music, telling a story, doing mental calculations, trying to remember something while driving, listening to a soccer match, etc.) while driving normally to the artificial mental tasks proposed in our experiment? Which part of these tasks is verbal and which is a spatial–imagery component? How does the effect of the mandatory component of the mental tasks in the experimental context compare with the spontaneous nature of normal mental activity? Despite the lack of answers to these questions, this first research on the effects of mental activity on driving suggests the convenience of raising drivers' awareness about the possible consequences of driving while their attention is focused on their own thoughts, unrelated to driving.

## References


Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin, 91,* 276–292.

Carpenter, P. A., & Just, M. A. (1978). Eye fixations during mental rotation. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 115–133). Hillsdale, NJ: Erlbaum.

Cowan, N. (1995). *Attention and memory. An integrated framework.* New York: Oxford University Press.

Crundall, D. E., & Underwood, G. (1998). Effects of experience and processing demands on visual information acquisition in drivers. *Ergonomics, 41,* 448–458.

Crundall, D. E., Underwood, G., & Chapman, P. R. (1997, September). *Peripheral detection rates in drivers.* Paper presented at the Seventh International Conference on Vision in Vehicles, Marselle, France.

Farah, M. J. (1985). Psychophysical evidence for a shared representation medium for mental images and percepts. *Journal of Experimental Psychology: General, 114,* 91–103.

Findlay, J. M. (1992). Programming of stimulus-elicited saccadic eye movements. In K. Rayner (Ed.), *Eye movements and visual cognition. Scene perception and reading* (pp. 8–30). New York: Springer.

Fuchs, A. F. (1976). The neurophysiology of saccades. In R. A. Monty & J. W. Senders (Eds.), *Eye movements and psychological processes* (pp. 39–53). New York: Wiley.

Gottlieb, W., Scherbarth, S., & Guse, K. (1996). New scientific instrument for vision in vehicles research. In A. G. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in vehicles V* (pp. 203–210). Amsterdam: North-Holland.

Hella, F., Neboit, M., & Laya, O. (1994). Les paramètres oculomoteurs comme indicateurs des exigences de surveillance en conduite automovile. *L'Analyse Ergonomique du Travail par l'etude de l'exploration visuelle* (pp. 151–156). Vandoeuvre, France: Institute National Recherché sur les Transports et leur Sècurité.

Henderson, J. M. (1993). Visual attention and saccadic eye-movements. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition. Advances in eye-movement research* (pp. 37–50). Amsterdam: North-Holland.

Hoecks, B., & Levelt, W. J. M. (1993). Pupillary dilatation as a measure of attention: A quantitative system analysis. *Behavior Research Methods, Instruments, & Computers, 25,* 16–26.

Huges, P. K., & Cole, B. L. (1988). The effect of attentional demand on eye-movement behavior when driving. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S. P. Taylor (Eds.), *Vision in vehicles II* (pp. 221–230). Amsterdam: North-Holland.

Jacobs, A. M. (1986). Eye-movement control in visual search: How direct is visual span control? *Perception and Psychophysics, 39,* 47–58.

Janisse, M. P. (1977). *Pupillometry. The psychology of the pupillary response.* New York: Wiley.

Johnston, J. A., & Dark, V. J. (1986). Selective attention. *Annual Review of Psychology, 37,* 43–75.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice Hall.

Karsh, R., & Breitenbach, F. W. (1983). Looking at looking: The amorphous fixation measure. In R. Groner, C. Menz, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and psychological functions: International views* (pp. 53–64). Hillsdale, NJ: Erlbaum.

Kosslyn, S. M. (1988, June 17). Aspects of a cognitive neuroscience of mental imagery. *Science, 240,* 1621–1626.

Land, M. F., & Horwood, J. (1996). The relations between head and eye movements during driving. In A. G. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in vehicles V* (pp. 153–160). Amsterdam: North-Holland.

Land, M. F., & Lee, D. N. (1994, June 30). Where we look when we steer. *Nature, 369,* 742–744.

Mannan, S., Ruddock, K. H., & Wooding, D. S. (1995). Automatic control of saccadic eye-movements made in visual inspection of briefly presented 2-D images. *Spatial Vision, 9,* 363–386.

McDowell, E. D., & Rockwell, T. H. (1978). An exploratory investigation of the stochastic nature of the drivers' eye movements and their relationship to the roadway geometry. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 329–345). Hillsdale, NJ: Erlbaum.

Miura, T. (1986). Coping with situational demands: A study of eye-movements and peripheral vision performance. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S. P. Taylor (Eds.), *Vision in vehicles* (pp. 126–137). Amsterdam: North-Holland.

Miura, T. (1990). Active function of eye-movement and useful field of view in a realistic setting. In R. Groner, G. d'Ydewalle, & R. Parham (Eds.), *From eye to mind. Information acquisition in perception, search, and reading* (pp. 119–127). Amsterdam: North-Holland.

Moray, N. (1990). Designing for transportation safety in the light of perception, attention, and mental models. *Ergonomics, 33,* 1201–1213.

Moray, N. (1993). Designing for attention. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness, and control* (pp. 111–134). Oxford, England: Clarendon Press.

Mourant, R. R., & Rockwell, T. H. (1972). Strategies of visual search by novices and experienced drivers. *Human Factors, 14,* 325–335.

Mourant, R. R., Rockwell, T. H., & Rackoff, N. J. (1969). Drivers' eye-movements and visual workload. *Highway Research Record, 292,* 1–10.

Näätänen, R. (1992). *Attention and brain function.* Hillsdale, NJ: Erlbaum.

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review, 86,* 214–255.

Norusis, M. J. (1993). SPSS for Windows. Advanced statistics (Release 6.0) [Computer software]. Chicago: SPSS, Inc.

Nunes, L. M., & Recarte, M. A. (1997). Argos program: Development of technological systems and research programs for driver behavior analysis under real traffic conditions. In P. Albuquerque, J. A. Santos, C. Rodrigues, & A. H. Pires da Costa (Eds.), *Human factors in road traffic II* (pp. 154–159). Braga, Portugal: Universidade do Minho.

Posner, M. I., & Raichle, M. E. (1997). *Images of mind.* New York: Scientific American Library.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85,* 618–660.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124,* 372–422.

Rayner, K., & Morris, R. K. (1990). Do eye-movements reflect higher order processes in reading? In R. Groner, G. d'Ydewalle, & R. Parham (Eds.), *From eye to mind. Information acquisition in perception, search, and reading* (pp. 191–204). Amsterdam: North-Holland.

Reeves, J., & Stevens, A. (1996). A practical method for comparing driver distraction associated with in-vehicle equipment. In A. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in vehicles V* (pp. 171–178). Amsterdam: North-Holland.

Rumar, K. (1990). The basic driver error: Late detection. *Ergonomics, 33,* 1281–1290.

Sanders, A. F., & Donk, M. (1996). Visual search. In O. Newman & A. F. Sanders (Eds.), *Handbook of perception and action. Vol. 3. Attention* (pp. 43–77). London: Academic Press.

Senders, J. W. (1983). *Visual sampling processes.* Hillsdale, NJ: Erlbaum.

Senders, J. W., Kristofferson, A. B., Levison, W. H., Dietrich, C. W., & Ward, J. L. (1967). The attentional demand of automobile driving. *Highway Research Record, 195,* 15–32.

Sheridan, T. B., & Ferrel, W. R. (1974). *Man–machine systems. Information, control and decision models of human performance.* Cambridge, MA: MIT Press.

Shinar, D. (1978). *Psychology on the road. The human factor in traffic safety.* New York: Wiley.

Summala, H., Nieminen, T., & Punto, M. (1996). Maintaining lane position with peripheral vision during in-vehicle tasks. *Human Factors, 38,* 442–451.

Theeuwes, J. (1993). Visual selective attention: A theoretical analysis. *Acta Psychologica, 53,* 93–154.

Theeuwes, J. (1995). Temporal and spatial characteristics of preattentive and attentive processing. In C. Bundesen & H. Shibuya (Eds.), *Visual selective attention* (pp. 221–233). Hillsdale, NJ: Erlbaum.

Theeuwes, J. (1996). Visual search at intersections: An eye movement analysis. In A. G. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in vehicles V* (pp. 125–134). Amsterdam: North-Holland.

Underwood, G., & Radach, R. (1998). Eye guidance and human information processing: Reading, visual search, picture perception, and driving. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 1–28). Oxford, England: Elsevier.

Van der Heijden, A. H. C. (1992). *Selective attention in vision.* London: Routledge.

Van der Heijden, A. H. C. (1996). Modularity and attention. In C. Bundebsen & H. Shibuya (Eds.), *Visual selective attention* (pp. 269–302). Howe, England: Erlbaum.

Von Helmholtz, H. (1962). *Physiological optics. Vol. 3* (3rd ed.; J. P. C. Southall, Trans.). New York: Dover. (Original work published 1860)

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63–102). New York: Academic Press.

Wickens, C. D. (1992). *Engineering psychology and human performance* (2nd ed.). New York: Harper & Row.

Wikman, A. S., Nieminen, T., & Summala, H. (1998). Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics, 41,* 358–372.

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