Accident Analysis and Prevention 36 (2004) 341–350

ACCIDENT ANALYSIS & PREVENTION

www.elsevier.com/locate/aap

Using mobile telephones: cognitive workload and attention resource allocation

Christopher J.D. Patten [a,b,*], Albert Kircher [c], Joakim Östlund [c], Lena Nilsson [c]

[a] *Stockholm University, S-106 91 Stockholm, Sweden*
[b] *Swedish National Road Administration, Vägverket, 781 87 Borlänge, Sweden*
[c] *VTI, Swedish National Road and Transport Research Institute, 581 95 Linköping, Sweden*

Received 30 October 2002; received in revised form 10 January 2003; accepted 17 January 2003

Abstract

Driver distraction is recognized as being one of the central causes of road traffic incidents and mobile telephones are tangible devices (among many other electronic devices) that can distract the driver through changes in workload. Forty participants completed a motorway route characterized by a low level of road complexity in the form of vehicle handling and information processing. A peripheral detection task (PDT) was employed to gauge mental workload. We compared effects of conversation type (simple versus complex) and telephone mode (hands-free versus handheld) to baseline conditions. The participants' reaction times increased significantly when conversing but no benefit of hands-free units over handheld units on rural roads/motorways were found. Thus, in regard to mobile telephones, the content of the conversation was far more important for driving and driver distraction than the type of telephone when driving on a motorway or similar type of road. The more difficult and complex the conversation, the greater the possible negative effect on driver distraction.

Keywords: Mobile telephones; Hands-free and handheld; Attention resource allocation; Workload

1. Introduction

With the era of the information society upon us, people are given ever-increasing opportunities to send and receive information. However, there are limits to man's attention, motor and perceptual resources. One recent example of an introduced communication tool is the mobile telephone, also referred to as a cellular telephone or cell phone. The present study will address the use of mobile telephones when driving. In particular, we want to explore mobile phones usage and their effect on cognitive workload and attention resource allocation needed for safe driving.

Evidence from studies of perceptual workload and visuocortical processing suggests that perceptual workload can modulate attention *focus* early in visuocortical processing (Handy et al., 2001). Furthermore, Handy et al. (2001) results also suggest that increasing the workload of the foveal targets decreases the amount of residual attention capacity available for allocation to task-irrelevant parafoveal locations. The parafoveal, or peripheral stimuli detection capacity, is important for the driver of a vehicle. If the driver feels a serious decrease of his/her attention capacity for driving the car, then he or she can reduce their vehicle's speed in a conscious or subconscious compensatory behaviour to the reallocation of their mental resources. Therefore, driving speed and perceptual stimulus detection capacity are important indicators of how mobile phone conversations may affect traffic safety when driving.

McKnight and McKnight (1993) studied conversation complexity and the effects on driver distraction in a low-fidelity driving simulator. Their results indicated that in simulated hands-free telephoning conversations, levels of complexity affected driver distraction. McKnight and McKnight also introduced elements of comparison between different situations such as tuning a radio and placing a call with detection rates that were relatively small but statistically significant. Different levels of secondary task and driving situations (e.g. primary task) complexity and their impact on the driver are important elements to be distinguished when considering the impact of 'secondary tasks' such as telephoning on driver distraction.

* Corresponding author. Fax: +46-243-75557.
E-mail address: christopher.patten@vv.se (C.J.D. Patten).

0001-4575/$ – see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0001-4575(03)00014-9

1.1. Purpose

For a decade or so, mobile telephones have been a focal point for traffic safety concerns from researchers and laymen. These traffic safety concerns have, however, had different loci of concern. A wide spread belief has existed, in particular by laymen, that driver distraction caused by mobile telephones lies in the mode of telephone, i.e. hands-free or handheld units. In fact, several OECD countries have even introduced legislation banning the use of handheld mobile telephone units when driving.

Driver distraction is recognized as being one of the central causes of road traffic incidents and mobile telephones are tangible devices (among many other electronic devices) that can distract the driver (Treat et al., 1979; Englund et al., 1998; Harbluk et al., 2000; Alm and Nilsson, 1995; De Waard, 1996; Zaidel et al., 1978; Martens and Van Winsum, 2000; see also NHTSA, 2000). Mobile telephone ownership and use has increased dramatically in recent years; from initially being large, cumbersome, expensive devices with exclusivity akinned with ownership, to being small, lightweight, inexpensive devices that now have universal ownership. The concern with driver distraction is of course the links to road traffic accidents. Where the causes of road traffic accidents may be many, driver distraction may only be one factor in the chain of many events leading to an accident. Moreover, the loci of the driver distraction may also vary greatly. However, in this study, our focus is on the driver distraction aspect of the *competition* over mental attention resources where the cognitive or mental workload is high.

The term 'driver distraction' would imply that the drivers do things that are not primarily relevant to the driving task (driving safely) and that this disturbs attention needed when driving safely. Consider the fact that humans have the ability of doing more than one thing at a time (e.g. walk and talk at the same time), then the problem of driver distraction for traffic safety must lie in the limitations of human attention resources and how the attention is allocated (prioritized) by the humans in their management of the different tasks, whether they are primary-task related (driving) or not. The allocation of mental resources, *attention*, is hinged to the different levels of driver (mental) workload (Wickens and Hollands, 2000; De Waard, 1996). Workload is defined as the amount of information processing resources (and limits there of) used for task performance (Wickens and Hollands, 2000; De Waard, 1996).The purpose of this study was, therefore, to explore the ability of drivers to cope with different levels of cognitive or mental workload that were introduced as secondary tasks and their effect on attention resource allocation. Moreover, the differences between hands-free and handheld mobile telephone units were also explored.

1.2. Scope

The scope of this study is restricted to a real traffic environment on public motorways and using two mobile telephone modes, hands-free and handheld. The hands-free unit had a separate microphone and loudspeaker and the handheld unit was simply held in the driver's hand while driving. The telephone conversations, per se, were examined and tasks such as dialing and other manual tasks were not included. The conversations were divided into two categories, simple and complex.

2. Method

To evaluate the workload of the participants whilst driving in a real-life field study, we used a secondary tasking methodology. Here, this means that the participants were asked to perform a high response-frequency parallel task (e.g. peripheral detection task (PDT) method) throughout the entire test route that was not relevant to the primary task of driving. The secondary task acts as an indirect indicator of mental workload. Secondary tasking, as a measure of cognitive workload, has been employed by a number of research groups within transportation research (e.g. Van Winsum et al., 1999; Crundall et al., 1999). Driving a vehicle is normally dominated by visual perception demands on attention, that is, 'successfully' driving a vehicle in traffic requires large amounts of mental resources (Hills, 1980). This is due to the fact that most of the information for safe driving needs to be gleaned from the driver's immediate physical environment—assuming that the driver is qualified and experienced. Other sources of information may be auditive, haptic or even olfactory, but to a lesser degree. Additional mental processes that need attention and may reduce attention capacity for driving come from perceptual interpretation, cognition, long-term memory processes, decision selection and decision execution (Wickens and Hollands, 2000).

Driving's close dependency on visual perception suggests that a visual secondary task would be appropriate because according to the multiple task theory (Wickens and Hollands, 2000), any increase or decrease of the visual demand will be more sensitive to changes in workload than to changes through other senses. Attention resources are multiple and in that sense multimodal tasks will only seriously compete for attention resources if the task draws on the same source, e.g. two separate visual tasks. Thus, when two tasks require attention from the same source, the human performance becomes more impeded than two tasks requiring different modes, e.g. visual and auditory (Wickens and Hollands, 2000; Harms and Patten, 2001). The peripheral detection task is a secondary visual task that has shown great sensitivity to mental workload level of drivers (Martens and Van Winsum, 1999; Olsson, 2000; Harms and Patten, 2001; Burns et al., 2000).

The route chosen for this field study was characterized by a low level of road complexity in the form of vehicle handling and information processing according to the taxonomy of complexity by Fastenmeier (1995) and van Benda et al. (1983). The road was a motorway section of the E4

(European inter-nation highway no. 4) with a maximum allowed speed of 110 km/h. The total distance used for this study was circa 74 km. The participants started travelling northbound from the city of Linköping to Norrköping (ca. 37 km). The participants turned off the motorway at an appropriate intersection on the E4 and drove the 37 km back to Linköping. The total driving time, including stops for the NASA raw task load index (NASA-RTLX) evaluations was approximately 1 h. The NASA-RTLX evaluations will be reported in a forthcoming study. (See Hart and Staveland (1988) and Byers et al. (1989) more details of the NASA-TLX and NASA-RTLX respectively.)

An acclimatisation section at the beginning of the route was ca. 7 km, with various speed limits used to make the drivers familiar with the experimental car. This extra-experimental section is not included in the total distance of 74 km, neither was any data from this section included in the data analyses.

The main reason for selecting a motorway section with a low/low classification, according to the taxonomy by Fastenmeier (1995) and van Benda et al. (1983), was to reduce the amount of 'noise' in the experimental data that might otherwise occur. That is, the motorway route chosen would have a low level of interactions with other road-users whom we experimentally would have no control over. Moreover, the data generated would also reflect a best-case scenario from a driver workload/distraction and a traffic safety perspective. Any additional complexity would exacerbate driver workload and thereby even traffic safety risks.

A taxonomic approach to describe information processing demands of traffic situations was proposed by Fastenmeier (1995) as mentioned above. Fastenmeier performed a detailed analysis of the classification scheme for traffic situations developed by van Benda et al. (1983). Fastenmeier highlights the following characteristics of traffic situations as crucial for complexity; the demands they put on drivers' information processing and/or vehicle handling capabilities. According to this approach, from a driver's perspective, traffic situations can be subdivided into the following four groups:

(1) High demands on information processing and high demands on vehicle handling: Typical examples from this group of situations are "driving within city centres" and complex intersections with road signs where the driver has to give right of way. In this paper, the authors term these route sections as having a "high-high" complexity.
(2) High demands on information processing and low demands on vehicle handling: Typical examples from this group of situations occur at intersections regulated by road signs and where the driver has the right of way. Other examples are entering or leaving a highway/motorway. These road sections are termed by the authors as having medium complexity.
(3) Low demands on information processing and high demands on vehicle handling: Typical examples from this group of situations occur on older, curvy rural roads or at intersections that are regulated by traffic lights. These road sections are also termed by the authors as having medium complexity.
(4) Low demands on information processing and low demands on vehicle handling: Low demands result from all those situations in urban and rural areas and on motorways where 'free driving', i.e. without interactions with other traffic participants, is possible. In this paper, the authors refer to these route sections as having a "low-low" complexity.

Definitions of the two telephone modes: Handheld—when a mobile telephone is held in the user's hand and positioned close to the ear. Hands-free—having a device consisting of a separate microphone and a separate loudspeaker connected to the mobile phone so that it is possible to talk on the phone without using a hand to hold it. However, depressing a button on the telephone itself will activate the telephone.

2.1. Materials and equipments

An instrumented vehicle was used in this study; a Volvo 850S, 2.5 l engine, manual gearbox and the model year 1996. The Volvo, an estate (or station wagon) version was, for the driver, apparently quite ordinary. The driver could not see any of the video cameras; they were concealed and also very small. All of the data collection equipment is in the boot of the Volvo. The sensors, etc., in the car are collected at a rate of 5 Hz and stored in an onboard laptop computer. The vehicle's cruise control was disabled.

The peripheral detection task equipment was built by Volvo Technical Development Corp.; the mobile telephone was a Nokia, model 6150 with a CARK 91 hands-free unit; the GSR and HRV instruments were from TEMEC (VITAPORT II).

The PDT equipment had been modified from the most recent PDT study at the Swedish National Road and Transport Research Institute (VTI) together with Volvo Development Corp. The PDT equipment comprises of a display with six red, light emitting diodes (LED) set in a display-panel, a modified micro-switch with increased depression-feedback and a computer unit for control, calibration of settings and data logging.

One diode at a time is illuminated, the selection of which is random. In the present study, the interval between illuminations of the LED signal was between 3 and 5 s, also at random within that range. The period of illumination is a maximum of 2 s unless the participant extinguishes the LED signal by depressing the micro-switch.

The light signals from the LED are reflected up onto the windscreen in the form of a head-up display. Prior to experimental trials, the stimulus intensity was adjusted to the individual participants and ambient lighting conditions (sun or clouds), to make sure that stimulus onsets could be detected while the driver looked out on the road scene. The LED reflections would appear approximately 6.8–21.8° left of the center of the steering wheel and approximately 3.8–5.3° elevated over the car console. The participants' performance was recorded in the form of PDT correct hit rate and their reaction times in milliseconds (ms).

2.2. Participants

The participants selected for this study were professional drivers (taxi drivers, couriers) with at least 3 years of holding a higher classification of drivers license. The age group requirements were from 21 to 60 years age and an annual mileage of at least 15,000 km. Professional drivers were selected because they have an established experience of driving and also usage of information technology (IT) systems in their vehicles, e.g. logistical systems, communication radios and/or mobile telephones. The participants were reimbursed for their participation with 100 € each. Forty participants completed the route. Eight were female and 32 were male. The mean age was 39.6 years and the mean annual mileage was 43,100 km.

2.3. Procedure and design

All the participants were instructed about the experiment and signed informed-consent forms regarding their liability and responsibilities when driving. Video footage consent forms were procured post-experimentally.

The participants were further instructed to drive, as they would 'usually' do, but to keep in mind their legal responsibilities regarding traffic violations. Training was also provided for the PDT and the mobile phone tasks prior to driving. All adjustments of seats, mirrors, coupe temperature and seat belts were done before leaving the VTI garage. Finally, the participants were instructed to prioritize the driving task first and respond to the light signals of the PDT diodes second.

Throughout the entire journey, a VTI technician was present in the test vehicle, sitting behind the driver. His role was to co-ordinate the phone calls, follow the design protocol, attach electronic markers to the vehicle data at predetermined points, to administer the NASA-RTLX subjective workload protocols and to deal with any problems. The participants were instructed to have no contact with the technicians during the driving tasks.

2.3.1. Peripheral detection task

The peripheral detection task was used in this study to evaluate the participants' workload whilst driving. The PDT task required the participants to react to a light stimulus (the LED) that appeared in the participants' periphery (in respect to the main driving focal point—straight ahead) and the light stimulus is illuminated for 2 s. The participants reacted by depressing the micro-switch attached to the left index finger. The LED, upon depression, subsequently extinguished. If the response is classified as 'correct' (response within 2 s), the reaction time was recorded in milliseconds (ms), otherwise the response was recorded as a late or missed response.

2.3.2. The mobile phone task

The participants were informed that they would receive an unspecified number of phone calls (eight phone calls in actual fact) during their drive. In one direction (outward or homeward), on the motorway to or from Norrköping, they were required to answer the mobile phone in either the handheld mode or the hands-free mode. The mobile phone was held in their right hand when using the handheld mode. The incoming call was 'opened' by pressing the "accept call" button on the phone. The same participant would after completing one route, change telephone modes. The order of use was balanced. The hands-free unit required only a depression of the "accept call" button on the telephone to 'open' the communication link. A microphone was attached to the roof above the driver's head for optimum sound quality and loudspeakers were also placed close to the driver's seat.

2.3.3. Conversation task

The conversation task was divided into three distinct levels of conversation; complex, simple and no conversations. The conversation task that was classed as complex, involved responding to questions that involved single digit addition and memory tasks. The research assistant read aloud (from a protocol) two single-digit numbers (e.g. 2 and 3) to the participants (via the mobile telephone). The participants were required to add the numbers and reply with their (correct) answers (i.e. $2+3 = 5$) conveyed verbally to the research assistant (their performance was recorded). After the first pair of numbers, only one single-digit number was read aloud to the participants (e.g. 4). This new number would then be added to the last number read out by the research assistant (in this case, 3). The correct answer (i.e. $3 + 4 = 7$) would again be conveyed verbally to the research assistant. The process was repeated with one single-digit number at a time, for a minimum period of 1 min and 30 s. This task required abstract thinking (mental arithmetic) and memory.

The simple conversation task required the participants to verbally repeat single digit numbers, which were read aloud to them by the research assistant (via the mobile telephone). The numbers were also read from a protocol.

The phone calls' duration was approximately 2 min, whereof the actual telephone task was a minimum of 1.5 min.

2.3.4. Data preparation

The first and last 400 m of the motorway drive were excluded, because these sections were used to accelerate up to cruising speed and respectively for decelerating, before exiting the motorway. Data for some shorter sections on the motorway, where temporary road works were registered (which

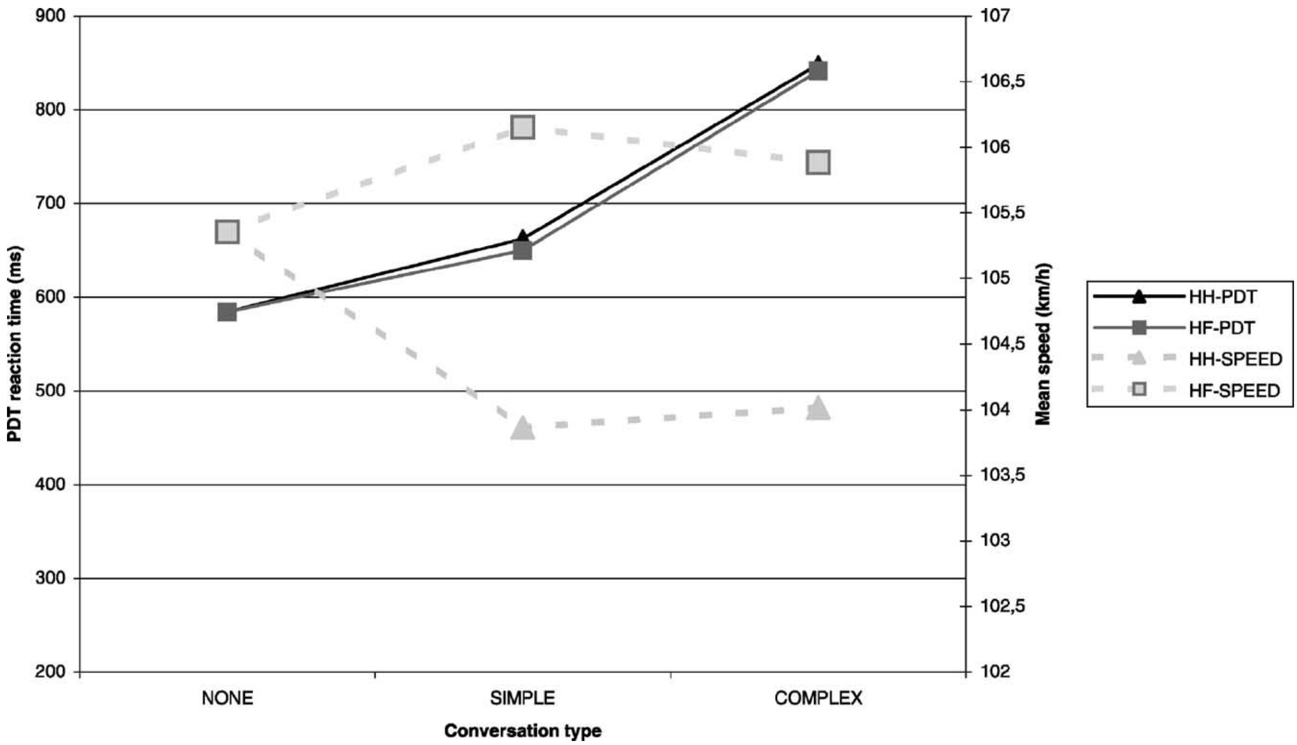

Fig. 1. Main results of field study; comparison of hands-free (HF) vs. handheld (HH) mobile telephones in different types of conversation complexity. Solid lines depict PDT reaction times and broken lines depict mean speed.

led to a speed decrease and traffic environment changes) for some of the participants, were also excluded.

3. Results

We compared effects of conversation type (simple versus complex) and telephone mode (hands-free versus handheld) to baseline conditions, that is, just driving situations. From the PDT data, we found a significant effect of conversation type but no effect on telephone mode. That is, the participants' reaction times increased when conversing but no benefit of hands-free units over handheld units on rural roads/motorways were found. The solid line in Fig. 1 represents the PDT reaction times in milliseconds (ms). The pair wise *t*-test analysis of the PDT reaction times between the simple conversation–task condition and the complex conversation–task condition for the hands-free telephone mode was significant ($t = -7.414$; d.f. = 39; $P \leq 0.001$). The PDT reaction times between the simple conversation–task condition and the complex conversation–task condition for the handheld telephone mode was also significant ($t = -8.036$; d.f. = 39; $P \leq 0.001$). The difference in PDT reaction times between telephone modes (i.e. hands-free and handheld) was not significant. The increase in reaction times from the baseline condition to the simple conversation–task condition for hands-free was significant ($t = 4.637$; d.f. = 39; $P \leq 0.001$) as was the handheld condition ($t = 3.964$; d.f. = 39; $P \leq 0.001$). The increase in reaction times from the baseline condition to the complex conversation–task condition for hands-free was significant ($t = 11.898$; d.f. = 39; $P \leq 0.001$) as well as the handheld condition ($t = 12.029$; d.f. = 39; $P \leq 0.001$).

Table 1
PDT reaction times and percentage increases

Conversation type	Mode	PDT reaction times (ms)	Mean PDT reaction times across modes (ms)	Overall percentage increase in reaction time over conversation type from 'none' condition (%)
None	–		584	0
Simple	HH	662***	656	12
	HF	650***		
Complex	HH	849***	845	45
	HF	841***		

HF: hands-free; HH: handheld; ***: significantly different ($P \leq 0.001$) from the 'none' condition.

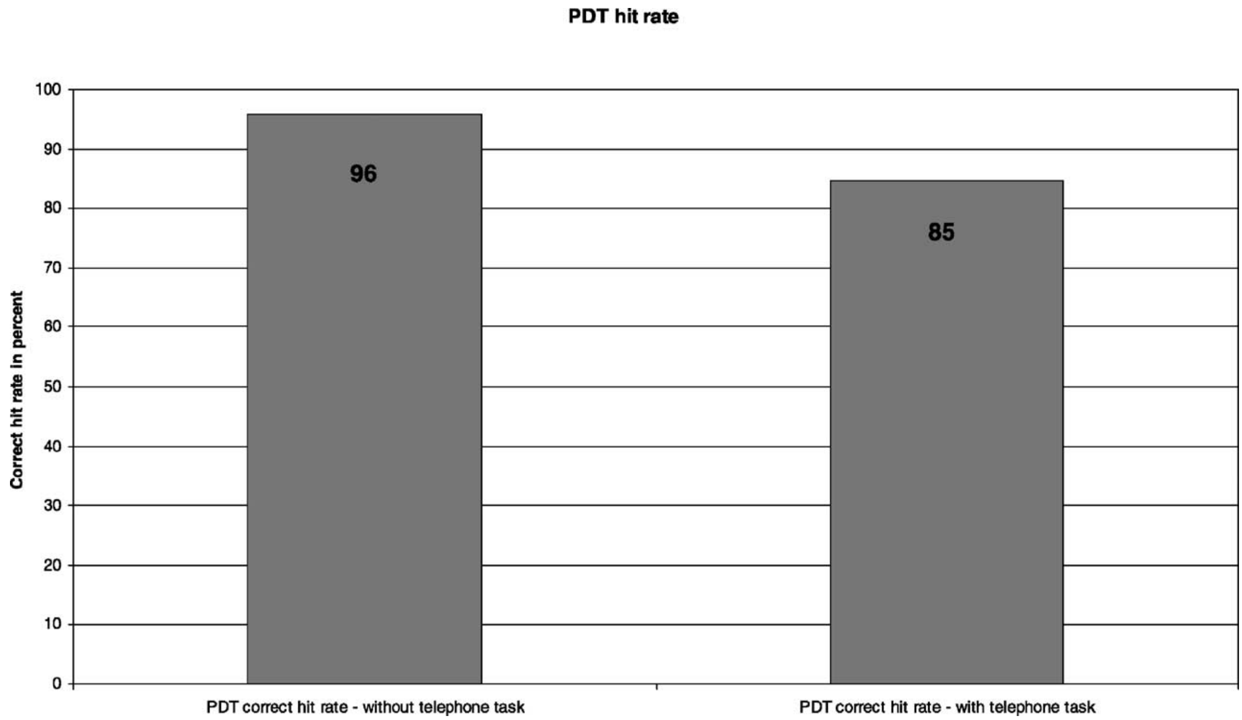

Fig. 2. PDT hit rate performance, expressed in percentage of correct responses, with mobile telephone tasks and without tasks while driving the motorway test route.

However, a significant effect on mean speed (broken lines in Fig. 1) could be related to telephone mode (hands-free and handheld) in pair wise t-test analyses. With handheld units the mean speed dropped, whereas the mean speed for hands-free was significantly greater than the mean speed for handheld units in the simple conversation–task condition ($t = 3.78$; d.f. $= 39$; $P = 0.001$), as in Fig. 1. The difference in mean speed between handheld and hands-free mobile telephones in the complex conversation–task condition was also significant ($t = 2.082$; d.f. $= 39$; $P = 0.04$). Increases in mean speed from the baseline (no conversation condition) up to the mean speed for hands-free units in the simple and complex conversation–task conditions were not statistically significant. The decreases in mean speed from the baseline condition to the handheld simple ($t = 3.009$; d.f. $= 39$; $P = 0.005$) and complex ($t = 2.22$; d.f. $= 39$; $P \leq 0.05$) conversation–task conditions were both significant.

In Fig. 2, the PDT hit rate performance is expressed in percentage of correct responses, i.e. a PDT reaction time <2.0 s. Fig. 2 shows the hit rate the telephone tasks and without telephone tasks while driving the motorway test route. The correct mean PDT hit rate without a telephone task was 96% and the correct mean PDT hit rate with a telephone task was 85% (paired t-test; $t = 5.982$; d.f. $= 39$; $P \leq 0.001$) (see Table 1).

Assuming that the driver detects a signal to stop (i.e. an impending traffic situation that could have a critical nature such as a large obstacle on the road ahead of them), the stopping distances are not greatly increased when engaging in the telephone tasks of this study, as seen in Tables 2 and 3. However, these reaction delays are calculated from the retardation in the detection of information (PDT reaction time). Also important for traffic safety is the percentage of misses, that is, when the participants failed to detect the visual information completely, as in Fig. 2. If this information had

Table 2
Stopping distances and reaction times at 110 km/h

Conversation type	‘Thinking time/distance’	Braking distance (m)	Total stopping distance (m)
None	17.9	75	92.9
Simple	20.1	75	95.1
Complex	25.9	75	100.9

‘Thinking time/distance’ is calculated by converting the PDT reaction time (ms) into m/s for the respective constant vehicle-velocities represented in distances (m) traveled while ‘thinking’. The distances (m) for ‘thinking time’ and actual braking are added together to give the total stopping distance in meters.

Table 3
PDT stopping distances and reaction times at 50 km/h

Conversation type	'Thinking time/distance'	Braking distance (m)	Total stopping distance (m)
None	8.1	14	22.1
Simple	9.1	14	23.1
Complex	11.7	14	25.7

'Thinking time/distance' is calculated by converting the PDT reaction time (ms) into m/s for the respective constant vehicle-velocities represented in distances (m) traveled while 'thinking'. The distances (m) for 'thinking time' and actual braking are added together to give the total stopping distance in meters.

been of a traffic safety-critical nature, then the impairment of attention caused by the telephone conversation would also thereby be critical in unfortunate circumstances. Moreover, the participants were aware that the PDT diodes would illuminate regularly and roughly where they could expect to see them. Visual information from the road scene that a driver would require could appear at anytime and from anywhere, even from behind, therefore, the traffic safety implications of the slowing or retardation of PDT reaction times has a greater significance than the absolute retardation in milliseconds.

'Thinking time/distance' is referring to the mental process of detection ("Is there something?"), perception ("There is something!"), cognition ("What is it?"), response selection ("What to do?") and response execution ("Do!"). 'Thinking time/distance' is calculated by converting the PDT reaction time (ms) into meters per second (m/s) and then into distance (m) for the respective constant vehicle-velocities represented in distances (m) traveled while 'thinking'. The distances (m) for 'thinking time' and actual braking (HM Stationary Office, 2001) are added together to give the total stopping distance in meters. In Table 2, the delay in 'thinking time/distance' between driving situations without a telephone task and with a simple conversation and a complex conversation task is 2.2 and 8.0 m respectively, at 110 km/h.

In Table 3, the delay in 'thinking time' between driving situations without a telephone task and with a simple conversation and a complex conversation task is 1.0 and 3.6 m, respectively, at 50 km/h.

The distances shown in Tables 2 and 3 are conditional to best possible situation scenarios, i.e. keen perception, best possible response selection, unfaltered response execution and optimal road friction. Anything less than the above will result in longer stopping distances.

The relationship between mean speed and the PDT reaction time data is important to establish. First, there was no significant relationship between mean speed and PDT reaction time for complex conversations. However, simple conversations produced significant relationships between mean speed and PDT reaction times. Figs. 3 and 4 illustrate the regression analysis between speed and PDT reaction times.

The regression between speed and the PDT reaction time for hands-free telephones in simple conversations in Fig. 3 is statistically significant (ANOVA; $F = 4.711$; d.f. $= 34$ $P = 0.037$).

The samples used in the regression analysis were trimmed at the uppermost and lowest levels of distributions for the PDT data and the mean speed data. Two cases had no or only partially recorded values. A total of six

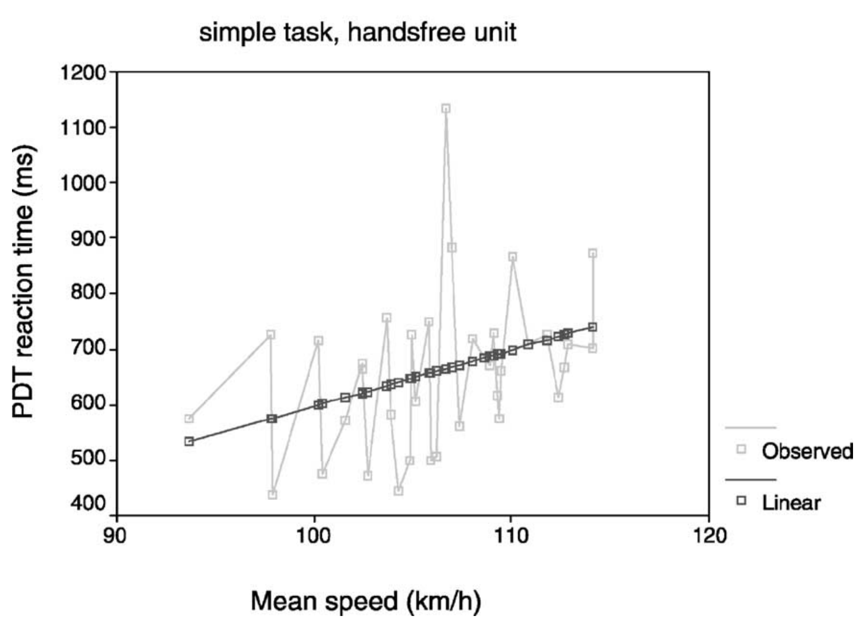

Fig. 3. Regression between mean speed, simple conversation type for hands-free (HF) and mean PDT reaction time for simple conversation type for hands-free mobile telephone equipment.

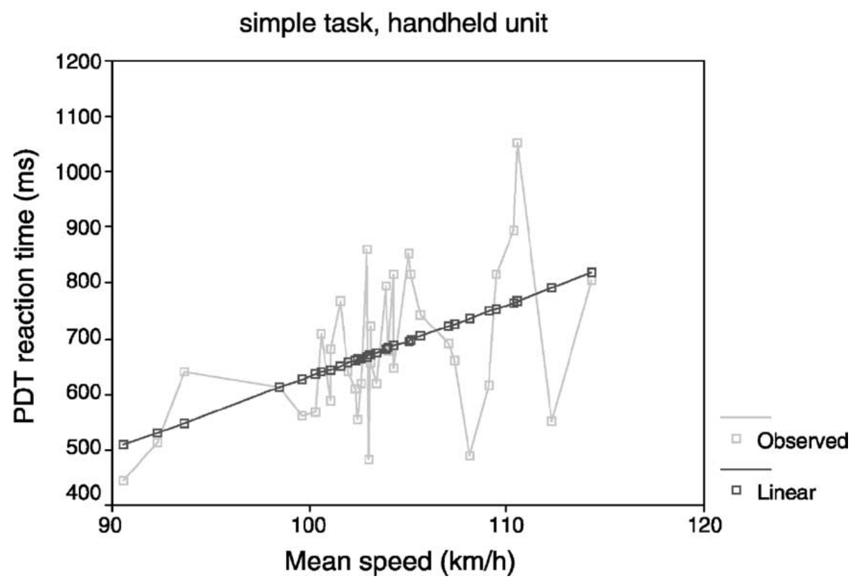

Fig. 4. Regression between mean speed, simple conversation type for handheld (HH) and mean PDT reaction time for simple conversation type for handheld mobile telephone equipment.

cases were thereby trimmed from the regression analysis data.

The analysis of variance in Fig. 4 for the regression between speed and the PDT reaction time for handheld telephones in simple conversations is also significant (ANOVA; $F = 11.183$; d.f. $= 34$; $P = 0.002$).

4. Discussion

The main findings of this study are that there is a significant effect of the task (conversation type) on the peripheral detection task performance (reaction time) but no effect of telephone modality (hands-free or handheld) on PDT performance. However, a significant effect of telephone modality was found on the dependent variable of mean speed. This is a very interesting finding because the PDT measure has been found to be a sensitive measure of cognitive workload as also found in Martens and Van Winsum (2000), Olsson (2000), Harms and Patten (2001) and Burns et al. (2000). The mean speed for the handheld units was significantly lower than the baseline mean speed whilst the mean speed for the hands-free units was significantly greater than the handheld unit and also greater (but not significant) than the baseline mean speed in both the conversation conditions (simple and complex).

The PDT reaction times increased by 45% from the baseline condition to the complex conversation condition as shown in Table 1. When converted to theoretical stopping distances, as in Tables 2 and 3, certain traffic safety considerations become apparent. When travelling at 110 km/h, a vehicle moves at 30.5 m/s. An average motorway lane in Sweden is ca. 3.75 m wide. At a rate of 30 m/s, even small lapses in concentration may result in alarming situations for the driver, especially if unexpected situations occur such as a slow moving vehicle in front of the driver. If, however, the mean reaction time for complex telephone tasks had a delay of 261 ms, then this ‘system retardation’ of the human brain may have a snow ball effect on the information detection, processing, analysis and the response execution. In this study, the mean PDT reaction time increased by 45% with complex conversations and thus the driver will also have (at least) 45% less time for detecting new information. In other words, the driver engaged in a complex conversation is appreciably less likely to detect changes in his/her traffic (road and vehicle) environment than when he/she is not distracted and can fully attend the primary (driving) task. Typically, this retardation of the driver’s information processing, in a road environment that has few ‘surprises’ (e.g. requiring a quick response) may well pass without any incident. However, in a complex road environment or in a situation requiring high levels of attention, this retardation in mental attention capacity will be much more apparent and may contribute to an incident.

The effect of telephone modality (hands-free and handheld) on mean speed in this study, as seen in Fig. 1, is difficult to explain and should, therefore, be followed-up by further research.

The participants’ workload level in this study imposed by driving and conversing, may have pushed towards a critical workload level for tackling multiple tasks, in the sense that they were not as sensitive to their *self*-imposed impediment, i.e. due to the increased workload and thereby their reduced capacity for performing a primary and a secondary task. Brought on in part by cognitive tunneling/capture and at the same time, in the case of the hands-free condition, a failure to compensate for the loss in attention resources for primary task activities (e.g. speed monitoring), the impediment’s subsequent result was no mean speed reduction and as indicated by Harbluk and Noy (2002), a visual scanning pattern with reduced monitoring of instruments. Moreover, when the participants were drawn into the conversation tasks they were forced to reprioritize their attention and in the case of the hands-free condition, to the detriment of the primary task of driving. Therefore, this increase in workload not only increased the PDT reaction times but would also appear to have fashioned a tendency to reduced speed awareness with no compensatory speed reduction behaviour in the condition for hands-free telephone units.

When using the handheld telephone unit (in contrast to the hands-free unit), the participants were constantly reminded of the secondary task (i.e. the telephone conversation) in the context of the primary task (of driving). The mean speed (broken line in Fig. 1) in the condition for the handheld telephone unit for the simple and complex conversation tasks were significantly lower than the baseline condition (i.e. no conversation, only driving) indicating a compensatory response from the participants. Astute readers may point out that even when there was a compensatory behavioral response to reduce visual information input through reduced speed, the recorded mean speed reductions in the handheld condition of this study were arguably not of a magnitude that would compensate for the reduction of attention to the primary task of driving safely, but what is important is the behavioral tendency of the drivers to compensate their increased workload level by reducing the vehicle's speed and maintaining a primary task awareness.

As mentioned above, cognitive capture or cognitive tunneling would also appear to arise as a result of increased or high workload. A similar tendency for cognitive capture was noted by Martens and Van Winsum (2000). The cognitive capture may have been somewhat interrupted when using the handheld telephone unit because of the psychomotor 'reminders' (e.g. an aching arm) coming from the participants hand and arm that supported the device. That is, when the participants used the handheld device they were reminded of their *self*-imposed impediment whereas when they used the hands-free device, they lacked any physical reminders despite the fact that in both telephone modes indicated a clear cognitive workload increase even with an induced conversation type that was 'simple'. Furthermore, cues in the peripheral vision in humans are important sources of information for judgement of speed (Samuelsson and Nilsson, 1996). This would therefore suggest that a reduction of the functional field of vision due to increased workload will also influence the drivers' ability to judge speed when under high mental workload. Another important function of the peripheral vision is that it also helps the driver by in part, directing or leading the visual scanning pattern. Recent eye-tracking studies have shown a greater tendency to fixate or reduce the visual scanning process when driving under higher workload (see Harbluk and Noy, 2002).

5. Conclusion

PDT reaction times indicate the human response time to detection and reaction of new information. However, the PDT reaction time cannot without additional assumptions be directly transferred to traffic safety accident risk comparisons. What it does say is that when participants are exposed to an increase in workload, the brain cannot process and react to new information at the same rate as situation with less workload.

When driving on motorways and larger rural roads, the mobile telephone modality would appear to be of little consequence when solely considering the conversational aspect of telephoning. Far more important for driver distraction, in regard to mobile telephones, is the content and the complexity of the conversation per se. Note that even simple conversations may distract the driver, however, the more difficult and complex the conversation, the greater the negative affect on the drivers' ability to allocate or direct their attention between tasks while driving.

Acknowledgements

This project was funded by the Swedish National Road Administration (SNRA). It was carried out jointly by VTI and the SNRA. Harry Sörensen, Beatrice Söderström, Janet Yakoub, and Susanne Gustafsson are gratefully acknowledged for their help with the instrumented vehicle and the data preparation, the recruitment and scheduling of the experiments participant's. Ola Svenson is also gratefully acknowledged for his guidance and comments on earlier versions of this paper.

References

Alm, H., Nilsson, L., 1995. The effects of a mobile telephone task on driver behaviour in a car following situation. Acc. Anal. Prev. 27, 707–715.

Burns, P.C., Knabe, E., Tevell, M., 2000. Driver behavioral adaptation to collision warning and avoidance information. In: Proceedings of the Congress, Santa Monica, IEA 2000/HFES2000: http://www.hfes.org.

Byers, J.C., Bittner, A.C., Hill, S.G., 1989. Traditional and raw task load index (TLX) correlations: are paired comparisons necessary? In: Mital, A. (Ed.), Advances in Industrial Ergonomics and Safety, vol. I. Taylor & Francis, London, pp. 481–485.

Crundall, D.E., Underwood, G., Chapman, P.R., 1999. Peripheral detection rates in drivers. In: Gale, et al. (Eds.), Vision in Vehicles, vol. VII. Elsevier, Exeter, pp. 261–269.

De Waard, D., 1996. The measurement of drivers' mental workload. Ph.D. thesis, University of Groningen, Traffic Research Centre, Haren, The Netherlands.

Englund, A., Gregersen, N.P., Hyden, C., Lövsund, P., Åberg, L., 1998. Trafiksäkerhet—en kunskapsöversikt. Studentlitteratur, Lund.

Fastenmeier, W., 1995. Die Verkehrssituation als Analyseeinheit im Verkehrssystem. In: Fastenmeier, W. (Ed.), Autofahrer und Verkehrssituation. Verlag TÜV Rheinland, Köln, pp. 27–78.

Handy, T.C., Solitani, M., Mangun, G.R., 2001. Perceptual load and visuocortical processing: event-related potentials reveal sensory-level selection. Psychol. Sci. 12, No. 3.

Harbluk, J.L., Noy, Y.I., 2002. The impact of cognitive distraction on driver visual behaviour and vehicle control, report no. TP13889E. Transport Canada, Ontario.

Harbluk, J.L., Noy, Y.I., Eizenman, M., 2000. The impact of internal distraction on driver visual behavior: http://www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/PDF/1.PDF.

Harms, L., Patten, C., 2001. Measuring distraction from navigation instructions in professional drivers—a field study with the peripheral detection task. In: Proceedings from 9th International Conference of Vision in Vehicles, Brisbane. Elsevier, Exeter.

Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock, P.A., Meshkati, N. (Eds.), Human Mental Workload. North-Holland, Amsterdam, pp. 139–183.

Hills, B.L., 1980. Vision, visibility and perception in driving. Perception 9, 183–216.

HM Stationary Office, 2001. The highway code. Prepared by the UK Department of Transport and the Central Office of Information, HMSO, London.

NHTSA, 2000. Internet forum on the safety implications of driver distraction when using in-vehicle technologies: http://www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/welcome.htm.

Martens, M., Van Winsum, W., 1999. Activation Criteria and warning strategies: driving simulator results. IN-ARTE Project (TR4014), ID 7.1. Unpublished technical report, TNO Human Factors Research Institute, Soesterberg.

Martens M., Van Winsum, W., 2000. Measuring distraction—the peripheral detection task. TNO Human Factors Research Institute, Soesterberg: http://www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/PDF/34.PDF.

McKnight, J.A., McKnight, A.S., 1993. The effect of cellular phone use upon driving attention. Acc. Anal. Prev. 25, 259–265.

Olsson, S., 2000. Measuring driver visual distraction with a peripheral detection task. Master thesis, ISRN LIU-KOGVET-D-0031-SE. Department of Behavioral Science, Linköping University, Linköping.

Treat, J.R., Tumbas, N.S., McDonald, S.T., Shinar, D., Hume, R.D., Mayer, R.E., Stansifer, R.L., Castellan, N.J., 1979. Tri-Level study on the causes of traffic accidents, Final Report, vols. I and II. US DOT HS-805-086 (NTIS PB 80-121064).

van Benda, H., Hoyos, C., Graf, Schaible-Rapp, A., 1983. Klassifikation und Gefährlichkeit von Verkehrssituationen. Bericht zum Forschungsprojekt 7320 der Bundesanstalt für Straßenwesen, Bereich Unfallforschung. Bergisch Gladbach.

Van Winsum, W., Martens, M.H., Herland, L., 1999. The effects of speech versus tactile driver support messages on workload, driver behaviour and user acceptance (TM-99-C043). TNO Human Factors, The Netherlands.

Wickens, C.D., Hollands, J.G., 2000. Engineering Psychology and Human Performance, 3rd ed. Prentice Hall, Saddle River, NJ.

Zaidel, D.M., Paarlberg, W.T., Shinar, D., 1978. Driver performance and individual differences in attention and information processing, vol. 1. Driver Inattention. Institute for Research in Public Safety, DOT-HS-803 793.