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Cognitive load and detection thresholds in car following situations: safety implications for using mobile (cellular) telephones while driving

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Abstract

This study was aimed at investigating drivers' ability to detect a car ahead decelerating, while doing mobile phone related tasks. Nineteen participants aged between 20 and 29 years, (2000–125 000 km driving experience) drove at 80 km/h, 50 m behind a lead car, on a 30 km section of motorway in normal traffic. During each trial the lead car started to decelerate at an average of 0.47 m/s^2 while the participant either looked at the car in front (control), continuously dialed series of three random integers on a numeric keypad (divided visual attention), or performed a memory and addition task (non-visual attention). The results indicated that drivers' detection ability was impaired by about 0.5 s in terms of brake reaction time and almost 1 s in terms of time-to-collision, when they were doing the non-visual task whilst driving. This impairment was similar to when the drivers were dividing their visual attention between the road ahead and dialing numbers on the keypad. It was concluded that neither a hands-free option nor a voice controlled interface removes the safety problems associated with the use of mobile phones in a car.

Keywords: Mobile phones; Cellular phones; Time-to-collision; Car-following; Cognitive load; Headway detection; Brake reaction time; Traffic safety

1. Introduction

During the last 10 years mobile or cellular telephones have gained wide acceptance in most developed countries, as they provide a relatively affordable and efficient solution to today's communication problems. In Finland, a country of less than 5.2 million people, mobile phones have become so popular that as of November 1997 there were over 2.0 million mobile service connections (information provided by Radiolinja Oy and Telecom Finland). While Finland has the highest user rates of mobile phones, the rate at which new connections are being made is still increasing, and other countries are also following this trend of an increasing rate of new connections. A phone poll of 670 drivers commissioned by the Central Organization for Traffic Safety in Finland in May 1997 (Liikenneturva, 1997) found that, indeed, 38% of the drivers had a mobile phone in their car, with 24% using it daily whilst driving and 14% only using it infrequently whilst driving. Of these drivers, 42% felt they had increased their risk of having crash at some time while using a phone in the car, with 25% reporting a decrease in their attention to the road and other traffic whilst on the phone. Not too surprising was that 57% of the drivers felt that mobile phones in cars increase traffic safety, because they gave the ability to call home rather than speeding when late, call emergency services to crash scenes, and report dangerous road or traffic conditions to authorities.

When considering whether having such a distraction as a mobile phone in a car is actually safe, we should examine all the elements of the phone task. Apart from the distracting task of dialing phone numbers and holding the phone when in use, there is also the distraction of conversation while driving.

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It is worth noting that conversing on a mobile phone is unlike conversing with a passenger. Passengers normally have the opportunity to perceive the road situation and can vary the demands or timing of their conversation. Of course they may also distract the driver, as suggested by the recent crash data from Doherty et al. (1998) but in their data the risk due to passengers is only increased in young drivers of age 16–19, possibly due to social interactions with peers; in adult drivers the presence of a passenger even tends to reduce risk. When conversing on a mobile phone the person outside the vehicle does not have the opportunity to perceive what is happening on the road ahead. It is therefore possible that they could put the driver at higher risk than passengers do by demanding his or her attention when it is needed to cope with a critical situation in the traffic flow (Piersma, 1993; Summala, 1997a).

When considering the problem of time-sharing mobile phone usage while driving, there has often been an assumption that because the two tasks are in separate modalities (verbal–auditory versus visual–spatial), and therefore using different cognitive resources, that there is little or no interference from the phone task on the driving task. However, this is not what multiple resource theory tells us. As Wickens (1992) notes, cross-modal resources will cause less interference in a dual task than intra-modal resources. This is not the same as causing no interference at all. So we should expect some inference from the phone task on the driving task. What is needed, is to determine specifically what functions of driving ability are impaired by such dual tasks, and whether this impairment poses an increased crash risk.

Crash data from around the world has shown two conflicting patterns for mobile phone related tasks. The National Highway Transportation Safety Administration (1997) reported that data from the Japanese Police showed that the majority of mobile phone related crashes occur during dialing or receiving calls. That is, when the driver would look at and manipulates the phone rather than the road ahead. In contrast, United States crash reports have shown that the majority of mobile phone related crashes occurred during conversation (National Highway Transportation Safety Administration, 1997). It is therefore evident that manipulating, looking at and talking into a mobile phone can all effect the risk of a crash.

Most traffic regulations used around the world that apply to mobile phones and driving have focused on the undesirable effect of manipulating a hand-held mobile phone while driving. The National Highway Transportation Safety Administration (1997) reviewed most of the current legislation from around the world on this issue. Victoria and New South Wales in Australia, Spain, Israel, Portugal, Italy, Brazil, Chile, Switzerland, Great Britain, Denmark, Hong Kong and Poland have all banned the use of hand-held mobile phone while driving. However, most governments have made no regulations at all specifically concerning the use of mobile phones whilst driving. They rely instead on the general regulations found in most traffic codes, such as, the driver's responsibility to give duty of care and attention to the roadway and other road users and being able to execute driving maneuvers freely and without delay.

Recent news stories highlight the current industry viewpoint on mobile phone technology in vehicles. Reuters (1997a) reported that Microsoft Corporation is targeting automobiles as a market for their Windows CE platform, to enable drivers to have access to personal organizers, address books and electronic mail whilst driving. Microsoft group vice president Paul Maruitz stated that '*You've got to keep your eyes on the road and your hands on the wheel*' so voice command technology can be used in the inferface to achieve this. It seems that *keeping your mind on the road* is not seen as a requirement in developing this system. These type of systems take mobile phone use a step further, using a more sophisticated computer interface, but will still add tasks to normal driving which will compete for the drivers attention. General manager for the Intel group, Ron Smith, admitted that such systems will raise questions about safety, but maintained that advanced computer interfaces in vehicles could be more helpful than distracting (Reuters, 1997b).

Three epidemiological studies have concluded that drivers who regularly use a mobile phone in their vehicle, including hands free phones, have an increased risk of having a road crash, including fatal crash involvement, compared to drivers who do not use mobile phones (Violanti and Marshall, 1996; Redelmeier and Tibshirani, 1997; Violanti, 1998). These studies did not report, specifically, what mobile phone use does to the driver that causes the increased crash risk. However, early experimental work has shown that perceptual and decision making tasks are impaired when a driver has to divide attention between the road and a car phone (Brown et al., 1969). Simulator studies which have used verbal, hands-free mobile phone tasks have found that the driver's reaction time to the onset of a lead car's brake lights were impaired during the tasks, especially amongst elderly drivers (Alm and Nilsson, 1994, 1995). On-road studies have shown that hands-free phones cause less interference to the driver's handling of the vehicle than hand held phones, however, hands-free phones still impair some aspects of driving performance (Brookhuis et al., 1991). Specifically, when drivers attempted to maintain a constant headway to a vehicle ahead and were engaged in a mobile phone conversation, their reactions to headway changes were somewhat delayed (Brookhuis et al., 1991; Brookhuis and

De Waard, 1994). There have also been three studies that have suggested that the intensity of the phone conversation is important, with more intense conversations adversely affecting driving performance (McKnight and McKnight, 1993; Becker et al., 1995; Briem and Hedman, 1995).

This study was aimed at investigating the performance of drivers in a safety critical sub-task, detecting a car ahead decelerating, while doing mobile phone related tasks. A number keypad task (visual divided attention) was used to simulate dialing a phone number, and a memory and addition task (non-visual attention) was used to simulate non-visual cognitive load associated with phone conversations. It was expected that both conditions would produce significant declines in detection performance when compared to driving without doing a visual or non-visual task.

2. Method

2.1. Participants

Nineteen participants (9 female, 10 male) were recruited from the University of Helsinki and the Helsinki Unemployment Center. The participants were aged between 20 and 29 years (mean 22.7, SD 2.49) and had lifetime driving experience ranging from 2000 to 125 000 km (mean 47 631 km). All participant's visual abilities met European standard licensing requirements (minimum static acuity of 0.6 and minimum visual field of 120 degrees).

2.2. Equipment

Two vehicles were used to collect driver performance data. The lead vehicle was a 1996 Skoda Felicia. The following vehicle was a 1994 Mitsubishi Galant equipped with a Mitsubishi multi-beam laser radar device able to measure inter-vehicle distance at a nominal accuracy of 0.1 m and a refreshing rate of approximately 25 Hz. The driver's use of controls, speed, between-vehicle separation, relative speed and lateral acceleration were recorded on a computer at 10 Hz. Four Panasonic WV-CD2 video cameras were used to record the road scene in front of the car (1), the driver's face (2), the driver's eyes (3), and the driver's hand movements on the console (4). The four views and the numerical data were mixed onto the same screen and stored on videotape. The following vehicle was equipped with additional brake and accelerator pedals for the experimenter in the passenger seat. The keypad on a prototype Nokia multifunction display system, mounted on the dashboard just to the right of the steering wheel, at an average of 35° (range 31.5–47.8°) eccentricity from the normal line of sight of the participants, was used in the mobile phone dialing task. The keys on the keypad were 6 mm high and 13 mm wide, with an inter-key spacing of 4 mm vertically and 2 mm horizontally.

2.3. Procedure

On-road testing was conducted on a 30 km section of Motorway 7 between Helsinki and Porvoo. The procedure followed that used in our earlier studies on the perception of the lead car's deceleration in peripheral vision (Summala et al., 1998; Lamble et al., in press). Each participant drove the following vehicle for 15 min prior to testing to allow them to become familiar with the vehicle. During testing an assistant drove the lead vehicle, while the participant drove the following vehicle 50 m behind with an experimenter, an experienced driving instructor, in the front passenger seat. The experimenter was responsible for attaining the correct headway and speed prior to beginning each trial and then engaging the cruise control to maintain a speed of 80 km/h. Participants were instructed to follow the lead vehicle, with their right foot positioned above the brake pedal and to brake as soon as they noticed the lead vehicle decelerating in each trial.

Three conditions were tested: a control task; a phone dialing task; and a cognitive task. Testing was conducted using blocks of ten trials of the same condition, starting with a block of the control task, for safety reasons, followed by a block of the cognitive task and a block of the phone dialing task. The three blocks were then repeated a total of three times, always starting with a block of the control task, producing 30 trials in each of the three conditions. (An additional control block actually completed the task but, unfortunately, it could not be used in the data analysis due to premature start of these trials by the experimenter: the distance and speeds were not yet balanced and the distance was still increasing at the moment of the disconnection of the cruise control.) The order of the two experimental conditions was balanced across participants in each replication of the blocks. The on-road sessions lasted approximately 90 min for each participant. In the control condition the participants were required only to focus on the lead vehicle. In the phone dialing task participants had to key in several series of three random integers (0–9), spoken by a second experimenter who was sitting in the rear passenger seat, on the keypad while focusing on the car ahead. The three integers were given when the driver had keyed in the last integer of the previous series, making the task self-paced. Series of three integers were given from the start of the trial until the driver made a brake response. In the cognitive task the second experimenter called out a series of random integers (1–9) one at a time, and the participants had to add the last 2 integers called (oral response) while focusing on the car ahead. This task was self paced to each participant, with the experimenter only calling out a new integer after the participant had responded to the last integer. Again, integers were given from the start of the trial until the driver made a brake response. The cognitive task was similar to that used by Gronwall (1977), Brookhuis et al. (1991), Summala et al. (1996), except being self-paced rather than forced pace, which enabled the participants to determine their own cognitive load.

The lead vehicle decelerated by the driver disengaging the cruise control while driving in fourth gear at 80 km/h. The average deceleration of the lead car during a trial was 0.47 m/s^2 (SD 0.19), calculated across all trials. The variance in decelerations were due to some variability in the slope of the road and the exact initial speed of the lead vehicle.

Approximately 4 weeks after driving, the participants were given two cognitive tests to measure their dual-task (parallel processing) ability. The first test was a gender free and educational level free, paper and pencil test developed by Baddeley et al. (1997) which provides an index of dual task performance (denoted MU by the authors). The participants were required to mark X's in a series of boxes located on a meandering line, whilst performing a self-paced memory span test. The second test was a modified version of the first test, which replaced the memory span task with the same adding task used in the on-road phase of the experiment.

3. Results

Detection thresholds were calculated using time-to-collision (TTC), see Fig. 1a, and brake reaction time (BRT), see Fig. 1b, and analyzed using a repeated measures ANOVA. Both measures were used because TTC has been a common measure in European research, while BRT more commonly reported in the North American research. TTC was calculated using the formula:

$$\mathrm{TTC} = ((v_r^2 + 2Ad)^{0.5}\,\Omega - v_r)/A$$

where: d, is the distance to the vehicle ahead; v_r, is the relative velocity of the vehicle ahead; and A, is the deceleration of the vehicle ahead.

BRT was defined as the time between the start of the lead car's deceleration and the participant's brake response, measured by the initial depression of the brake pedal.

There was a significant main effect of the experimental condition, both in TTC ($F_{2,36} = 6.71$; $P < 0.01$) and in BRT ($F_{2,36} = 12.63$; $P < 0.001$). The difference between the control condition and the secondary tasks across all replications was an increase in TTC threshold by an average of 0.62 s for the phone dialing task ($F_{1,18} = 4.16$; $P = 0.056$) and 0.95 s for the cognitive task ($F_{1,18} = 20.26$; $P < 0.001$), and an increase in BRT by an average of 0.48 s in the phone dialing task ($F_{1,18} = 17.72$; $P < 0.001$) and 0.50 s in the cognitive task ($F_{1,18} = 17.37$; $P < 0.001$). There was no significant effect for the blocks of replications for either measure ($F_{2,36} = 0.08$; $P = 0.922$ for TTC; $F_{2,36} = 1.91$; $P = 0.162$ for BRT) and no significant interaction between type of task and replication ($F_{4,72} = 0.47$; $P = 0.760$ for TTC; $F_{4,72} = 0.74$; $P = 0.669$ for BRT).

There were some differences between the sample pools (tertiary students versus non-tertiary student unemployed) in TTC thresholds ($F_{1,17} = 3.00$; $P = 0.102$ for the main effect of group, $F_{2,34} = 4.84$; $P < 0.05$ for the interaction of task type by group), but not in BRT ($F_{1,17} = 0.01$; $P = 0.908$ for the main effect of group,

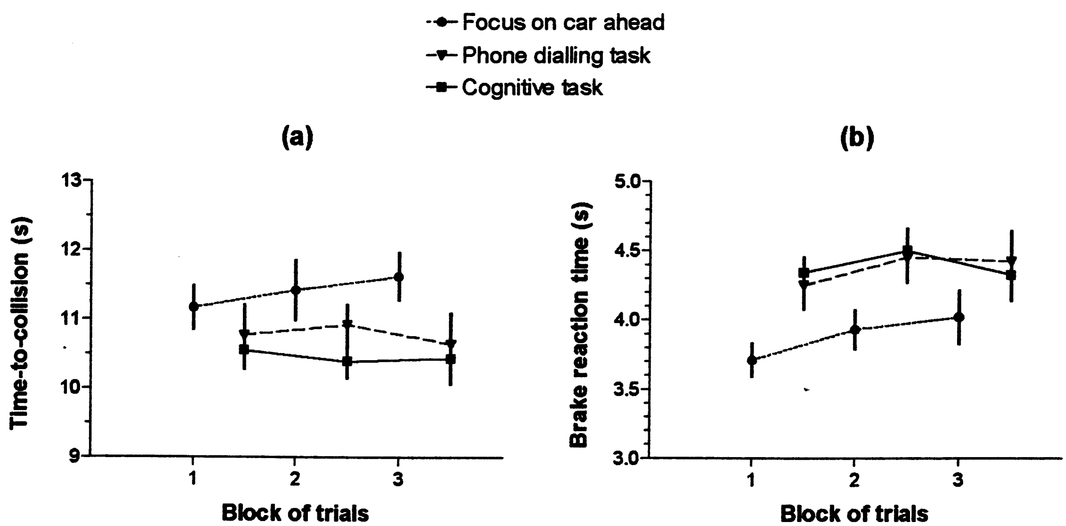

Fig. 1. Mean detection thresholds and standard errors for the three task conditions and the three replications, in terms of (a) TTC and (b) BRT.

Table 1
Summary of research findings on mobile phones and distance keeping

Study	Type of study	Primary driving task	Secondary task/driver condition	Response latency (age)
Brookhuis et al. (1991)	On-road	Keep constant distance to lead car	Forced pace memory test via mobile phone[a]	0.6 s (23–65 years)
Alm and Nilsson (1995)	Simulator	Brake when lead cars brakes	Memory and comprehension test[b] via mobile phone	0.56 s (<60 years) 1.46 s (>60 years)
Current study	On-road	Brake when lead car decelerates (reduces headway)	Phone dialing task and self paced memory test[a]	0.48 s and 0.50 s (20–29 years)

[a] Paced Auditory Serial Addition Task (Gronwall, 1977)
[b] The Working Memory Span Test (Baddeley et al., 1995)

$F_{2,34} = 1.75$; $P = 0.189$ for the interaction of task type by group). Post hoc analysis revealed that student's TTC thresholds were higher in the phone dialing condition, than the non-student's ($t_{17} = -2.366$; $P < 0.05$). We believe this difference was caused by the fact that the unemployed group had more experience in using mobile phones, especially in a car, than the student group, and were therefore more practiced at the divided attention dialing task.

The control of lateral lane position during each trial was estimated by analysis of the standard deviation of lateral acceleration (SDLA), however there was no effect for the type of task on SDLA ($F_{2,36} = 2.16$; $P = 0.130$). During the phone dialing task the participant's average glance duration, defined as the time the gaze was in the area of target, to the roadway was 1.25 s (range 0.65–2.03, SD 0.36), and the average glance duration to the keypad was 0.79 s (range 0.52–1.23, SD 0.22). During the cognitive task conditions the participants received, on average, a total of 185 addition tasks, and averaged a total of ten errors and 21 omissions.

4. Discussion

The results indicated that drivers' detection ability in a closing headway situation was impaired by about 0.5 s in terms of brake reaction time and almost 1 s in terms of time-to-collision, when they were doing a non-visual cognitive task whilst driving. This impairment was similar to when the same drivers were dividing their visual attention between the road ahead and dialing series of random numbers on a keypad. Table 1 compares the results of the current study to previous research on response latencies in brake reactions, which have used different methodologies. The current finding of a 0.5 s increase in response latency in brake reactions is similar to the 0.6 s latency found by Brookhuis et al. (1991) and the 0.56 s latency for younger drivers reported by Alm and Nilsson (1995). It is worth noting that this latency is around three times larger than the deterioration De Waard and Brookhuis (1991) found for drivers under the influence of alcohol, with the driver's blood alcohol concentration (BAC) decreasing from 0.046 to 0.034% over the course of the drive. Since this BAC is the 'just legal' BAC category in most countries today, reflecting a 0.05% legal limit, it could be considered that any impairment beyond that found at this BAC is unacceptable to traffic safety.

It should be remembered that the measured detection thresholds in the current study represent the optimum performance of alerted drivers in a dual task situation. These thresholds do not include the normal motor response component of moving the foot from the gas pedal to the brake pedal of about 0.2 s and the 0.2 s latency before the brakes respond at full power (Shinar, 1978; Cohen, 1987). Driver's reaction times in non-experimental situations could be expected to include an additional latency due to alertness (see Johansson and Rumar, 1971; Olson and Sivak, 1986).

Due to availability of equipment the driver's control of lateral lane position was only analyzed by the standard deviation of lateral acceleration (SDLA), which does not control for road curvature during trials, and no impairment was found during the phone tasks. Brookhuis and De Waard (1994) similarly found that standard deviation of steering wheel movements (SDSW) was unaffected when drivers were using mobile phones during quiet motorway traffic and the standard deviation of lateral position actually decreased. However, they found that SDSW increased dramatically when the drivers used even a hands-free phone on a busy ring road or in city traffic. In the current study there were some very noticeable lateral movements during the cognitive task for a few of the participants, indicating a tendency for them to weave inside the lane whilst doing the secondary tasks. This may reflect individual aspects of driving ability or driving style related to the experience of specific drivers. By comparison all the individual participants displayed a similar pattern of impairment in detection thresholds, with both secondary tasks producing higher thresholds than when only looking at the car ahead. It is therefore suggested that additional research is needed to assess the impact of secondary cognitive tasks on safe lane keeping performance amongst different types of drivers, such as novice, elderly or crash prone drivers, on different types of roads with various traffic volumes (for example see Wikman et al., 1998).

The tasks given to drivers in this study were not, of course, representative of all the ways that mobile phones are being used in cars. They were selected in a way to ensure that mental load was approximately constant throughout each trial. Mental load in a normal conversation typically fluctuates too much to allow strict experimental control. On the other hand, although keying in dictated phone numbers in groups of three digits may not be the most frequent operation it however occurs.

The conclusion of the current study is that neither a hands-free phone option nor a voice-controlled interface removes the problem of driver performance impairment when using a mobile phone in the car. What is needed, as a minimum improvement, is an increase in road user education to make drivers aware of the risks involved with using phones whilst driving even with a hands-free option. Given the current level of mobile phone usage in vehicles, it is apparent that drivers are able to use a mobile phone while driving, but it's use is an attention demanding factor which is likely to contribute to a crash in a critical situation. The present and past experimental results, as compared to alcohol effects noted above, and reported crashes where the responsible driver was distracted through the use of a mobile phone (e.g. European Road Safety Federation, 1997), imply that mobile phones in cars represent an unacceptable increase in the risk of having a crash. This problem has already been recognized in Ohio, USA, where the State Highway Patrol and Ameritech, a cellular phone company, are supporting a 'Keep Your Mind on the Drive' advertising campaign which aims at educating drivers to the dangers of in-car distractions (Associated Press, 1997).

A Generic Intelligent Support Driver Support (GIDS) system was already proposed and investigated in the European Drive I project (see Michon, 1993) which addressed many of the safety issues of increasing technology in road vehicles. However, while waiting for the development of such intelligent vehicle systems, which will automatically postpone the connection of incoming calls when a driver is loaded by other traffic (see Piersma, 1993), telecommunication companies and manufacturers of mobile phone car accessories need to provide the ability for incoming callers to know that they are phoning the driver of a vehicle, allowing them the opportunity to call later or for the driver to call back at a more appropriate time, and allowing the driver more time to answer incoming calls without being distracted by continuous ringing tones (Summala, 1997b). It is clear that the communication and computing industry will be increasing the availability and complexity of in-car equipment that will utilize the driver's non-visual cognitive resources. It is also clear that, with the current growth in communications and information technologies, there is a need for international standards on driver performance limits caused by in-car devices, or at least an agreed framework for assessing the impact on driver safety that such devices may have. The lack of such standards or framework should be considered as a lapse in traffic safety management by regulating or governing bodies whose function it is to promote crash reduction strategies in its various constituent members.

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