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Real-world effects of using a phone while driving on lateral and longitudinal control of vehicles

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ABSTRACT

Introduction: Technologies able to augment human communication, such as smartphones, are increasingly present during all daily activities. Their use while driving, in particular, is of great potential concern, because of the high risk that distraction poses during this activity. Current countermeasures to distraction from phone use are considerably different across countries and not always widely accepted/adopted by the drivers. *Methods:* This study utilized naturalistic driving data collected from 108 drivers in the Integrated Vehicle-Based Safety Systems (IVBSS) program in 2009 and 2010 to assess the extent to which using a phone changes lateral or longitudinal control of a vehicle. The IVBSS study included drivers from three age groups: 20–30 (younger), 40–50 (middle-aged), and 60–70 (older). *Results:* Results from this study show that younger drivers are more likely to use a phone while driving than older and middle-aged drivers. Furthermore, younger drivers exhibited smaller safety margins while using a phone. Nevertheless, younger drivers did not experience more severe lateral/longitudinal threats than older and middle-aged drivers, probably because of faster reaction times. While manipulating the phone (i.e., dialing, texting), drivers exhibited larger lateral safety margins and experienced less severe lateral threats than while conversing on the phone. Finally, longitudinal threats were more critical soon after phone interaction, suggesting that drivers terminate phone interactions when driving becomes more demanding. *Conclusions:* These findings suggest that drivers are aware of the potential negative effect of phone use on their safety. This awareness guides their decision to engage/disengage in phone use and to increase safety margins (self-regulation). This compensatory behavior may be a natural countermeasure to distraction that is hard to measure in controlled studies. *Practical Applications:* Intelligent systems able to amplify this natural compensatory behavior may become a widely accepted/adopted countermeasure to the potential distraction from phone operation while driving.

1. Introduction

In the last decade, mobile phone use has led to rising concerns about distraction during driving. Although phone use while driving has been widely addressed by researchers (McCartt et al., 2006) and legislative actions in several countries, a comprehensive examination of its effect on driving performance in real traffic has not been performed. Agreement on the most promising countermeasures to address potential distraction posed by phones and legislation is even farther away. In addition, current countermeasures are not always widely accepted or adopted by the drivers. For example, bans on phone use have been shown to provoke unsafe driving behaviors (Gauld et al., 2014).

Current legislation related to phone use while driving ranges from total prohibition, as in Japan, to ban of hand-held devices, as in most of Europe and several states in the United States, to no limits on conversation, as in Sweden. In some jurisdictions, special restrictions apply to specific types of drivers (e.g., young or professional drivers). The variety of legislations around the world may, in part, reflect the lack of a common understanding about the effect of cell phone use on vehicle control.

Research on phone use while driving employs several types of data, both subjective and objective. These include questionnaires (Backer-Grondahl & Sagberg, 2011), interviews (Brusque & Alauzet, 2008), crash databases (Redelmeier & Tibshirani, 1997; Violanti, 1998; McEvoy et al., 2005), driving simulators (Horberry et al., 2006), real traffic observations (Taylor et al., 2007, Vivoda et al., 2008), test tracks (Hancock et al., 2003), and naturalistic studies (Hickman & Hanowski, 2012). With the exception of naturalistic driving studies, most of the other aforementioned studies report that all uses (including talking) of cell phones while driving increase risk.

Different types of data may suffer from different biases and consequently produce results that are difficult to reconcile. For instance, subjective data from interviews and questionnaires may be guided by crash

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databases, in which only crash-involved drivers are included. Research also shows that drivers who use the phone while driving are more likely to have a prior history of citation and crash involvement (Beck et al., 2007), thus potentially biasing crash databases. In addition, phone users may be inclined, correctly or not, to attribute the crash to mobile phone use when asked after the fact (Backer-Grondahl & Sagberg, 2011).

Data from driving simulators and test tracks offer the unique opportunity to safely and repeatedly provoke critical situations. However, participants in these controlled conditions may accept higher levels of risk than they would in reality, especially if asked to do so by the researcher before they are fully acquainted with the environment (Hancock et al., 2003). In contrast, Schömig and Metz demonstrated that participants in driving simulators select lower levels of risk if they are allowed to compensate for phone distraction by, for instance, stopping the vehicle (Schömig & Metz, 2012); furthermore, Shinar showed that repetition reduces the negative interference of distraction due to phone use (Shinar et al., 2005).

Studies based on crash databases and observational studies have the great advantage of anchoring the results to the real world, and the disadvantage of dealing with complex biases while showing only correlational, but not causal, relationships. For instance, naturalistic studies only include *volunteers* who may not come from a random population. Among others, one advantage of *naturalistic driving studies* is that they allow drivers to be compared to themselves when on or off the phone so that possible compensatory behavior when using a cell phone may be assessed. Naturalistic data also offer the opportunity to analyze different driver age groups and have been successful in explaining how experience modulates driving behavior (Lee et al., 2011). Thus, the analysis of naturalistic data seems to offer the best opportunity to advance our understanding of the effect of using a phone while driving, especially in very large datasets.

The present study used a large naturalistic driving data set to investigate (a) how changes in driver behavior might arise from two opposing components, distraction and driver compensatory behavior; and (b) how these components are balanced.

2. Methods

The data used in this study, from the IVBSS Field Operational Test (FOT) (Sayer et al., 2011), were collected from 108 randomly sampled passenger-car drivers in 2009 and 2010. Drivers were equally distributed in three different age groups: 20–30 (younger), 40–50 (middle-aged), and 60–70 (older). For each age group, the number of female and male drivers was the same. In order to qualify for the study, participants were required to drive not less than 25% below the National Personal Transportation Survey reported average for their age and gender category. Further, drivers who had any felony motor vehicle convictions, such as driving while intoxicated or under the influence of alcohol, within 36 months of recruitment were excluded from the study. Data were collected using 16 Honda Accords, which were equipped with several advanced safety systems, including forward collision warning, lane departure warning, and blind-spot detection. The vehicles were rotated among the drivers, and each driver was unsupervised while pursuing her/his normal driving behavior for 40 days. In this study, drivers used their personal phones, and records were not kept as to the types of phones that drivers used. In 2006–2007 Honda Accords, there was not an option to sync a driver's phone to the research vehicle. If drivers did use their phones in a hands-free manner, they did so with their personal hands-free equipment (e.g., a headset).

Throughout the study, driving and video data, including warning-system triggers (silent alerts) from the vehicle's active safety systems, were collected continuously. However, the safety warnings were not presented to the drivers until after the 12-day baseline period had elapsed. Data collected included longitudinal radar information (range and range rate), vehicle dynamics (e.g., speed and lateral velocity), and lane offset. Five video-cameras recorded forward scene, driver's face, in-cabin view of the controls, and rear scene (two cameras). Video data were recorded continuously at 10 Hz.

The present study only used IVBSS data from the baseline period, in order to assess the effects of engaging in a conversation or manipulating a cell phone on driving performance without the safety warnings. Video data for all drivers in the first week of data collection were manually coded for cell phone use. A total of 3519 segments of data in which the driver was either engaged in a phone conversation (Talk) or manipulating a phone, that is, interacting visually and manually with a phone (Manip), were identified in the dataset (Funkhouser & Sayer, 2011). The average duration of these data segments was 70 s; 86% of the segments were shorter than 2 min; 4% of the segments were longer than 5 min. For all Manip and Talk segments, two matching baseline segments were identified: the Pre-Phone segment, in the 5 min preceding the phone segment; and the Post-Phone segment, in the 5 min following the phone segment (Phone). Baseline segments had to have the same duration as the corresponding phone segment, and an average vehicle speed within 25% of the phone segment's average speed. This speed filter helped keep the context similar between phone and baseline segments and was not sufficiently selective to mask the possible effect of cell phone use on speed. In fact, changes in speed from cell-phone use are reported to be much smaller than 25% in several studies (Haigney & Westerman, 2001; Jenness et al., 2002; Charlton, 2004; Shinar et al., 2005). Baseline segments were not permitted to contain any phone use. For 1033 of the identified Phone segments from 91 different drivers, it was possible to find the two comparison baselines. All other phone segments (2487) were excluded from analysis. Of the three criteria, the speed-match criterion was the most stringent, responsible for the exclusion of most of the phone segments from analysis. The duration-match criterion mainly precluded phone segments of longer duration; however, since these segments were rare from the beginning, this selection is not likely to have biased the analysis. Exclusion of phone segments because the baseline periods also included phone use occurred only rarely.

For the Pre-phone, Phone, and Post-Phone segments, four indicators of driver performance were selected. Two indicators were related to the longitudinal control of the vehicle: minimum time-to-collision (MinTTC) and median headway (MedHW). The two remaining indicators were related to the lateral control of the vehicle: minimum time-to-lane-crossing (MinTLC) and maximum lane offset (MaxLO). Time-to-collision is a longitudinal safety indicator used in commercial safety systems and collision mitigation systems to issue forward collision warnings and initiate autonomous braking (Kaempchen et al., 2009). Thus, MinTTC represents the highest longitudinal risk taken by the driver during each data segment or, in other words, the limit of the driver's longitudinal safety margin. Time-to-collision was computed as the ratio of the distance between the driver's vehicle and the one ahead and their relative speed; both these measures were obtained from a forward-looking radar. MedHW, an indicator of driver car-following behavior, has been successfully used to compare driver performance across different driving and distraction conditions (Rakauskas et al., 2008). MedHW complemented MinTTC by indicating the usual longitudinal safety margin of the driver.

Time-to-lane-crossing is a lateral safety indicator used in commercial safety systems to initiate lane departure warnings and, in current research projects, to control automated steering (Mammar et al., 2006). Thus MinTLC represents the highest lateral risk taken by the driver during each data segment or, in other words, the limit of the driver's lateral safety margin. Time-to-lane-crossing was computed as the offset from the center of the lane divided by the lateral velocity, using car width, lane width, lateral offset, and lateral velocity. Time-to-lane-crossing was calculated only when lateral speed was available and greater than 0.2 m/s in either direction. The direction of the lateral velocity determined whether to use the distance to the left or to the right lane edge to compute lateral offset.

MaxLO is an indicator of driver lane-keeping behavior, measuring how closely the driver keeps the car in the middle of the lane. MaxLO was preferred to the more common standard deviation of lane position because the latter is very sensitive to the segment duration when segments are as short as the ones analyzed in this paper (Dozza et al., 2013). Further, MaxLO is more sensitive than standard deviation of lane position in showing whether the drivers position themselves differently in the lane and less affected by overtaking maneuvers. MaxLO was processed using the lane offset information from the IVBSS lane departure system. Larger values of MaxLO are associated with positions closer to the road curb in that data segment.

Correlation analysis was performed to verify the extent to which the dependent measures MinTTC, MedHW, MinTLC, and MaxLO were associated with each other. Linear mixed models (LMM) were used to model each dependent measure as a function of predictors. For each analysis, three predictors were considered: *age group* (Younger, Middle-aged, Older), *task type* (Talk vs. Manip), and *time* (Pre-Phone, Phone, and Post-Phone). Because non-central measures tend to vary with the length of the segment, segment duration was used as a covariate in the model.

Data were analyzed using Matlab © and the NatWare software (Dozza 2013). Statistical analysis was performed using SAS PROC MIXED. In each mixed model, driver, interactions between driver and within-driver predictors (e.g., task), and events nested in driver were treated as random effects. Denominator degrees of freedom were estimated using the Kenward–Roger method (Kenward & Roger, 1997). This approach ensures that comparisons are made among matched segments and that within-driver correlation is accounted for. Threshold for significance was set to $p = 0.05$. Four mixed models, one for each dependent measure, were developed using PROC MIXED. Each model started with age group, task, time, and all interactions among those variables as fixed effects. Segment duration and interactions with each predictor were included as covariates. Random effects included driver, interactions between driver and all predictors except age group, and event nested in driver. Non-significant fixed effects and their corresponding random effects were removed one at a time in backwards-stepwise fashion.

3. Results

3.1. Descriptive statistics

Of the 91 drivers in the analysis, 35 were younger, 34 middle-aged, and 22 older. Younger drivers contributed 65% of the analyzed tasks, middle-aged driver 29%, and elderly drivers 6%. 69% of the analyzed tasks were phone interactions (Manip) and 31% were phone conversations (Talk). Young subjects were responsible for 71% and 51% of the Manip and Talk tasks, respectively; for middle-aged drivers the figures were 25% and 38%, and for older drivers, 4% and 11%. Average Talk duration was 42.8 s, and average Manip duration was 39.8 s; both demonstrated monotonic decreasing distributions (see Fig. 1). 90% of Talk tasks and 93% of Manip tasks were shorter than 2 min.

Correlations among dependent variables across all segments are shown in Table 1. Only the two lateral control measures (MinTLC and MaxLO) are correlated to any degree. The raw correlation between these two measures is −0.40. Although results of analyses of these two measures are likely to be similar, both were analyzed separately since there was substantial unshared variance remaining (84%).

Not all indicators were available for all segments. Specifically, MinTTC and MedHW could be calculated only if there was a vehicle in front, and MinTLC was calculated only when lateral speed was available and greater than 0.2 m/s in either direction. MaxLO was calculated for all segments. Table 2 shows the proportion of data available for the different dependent measures. Available data are also broken down by age group, task, and time categories.

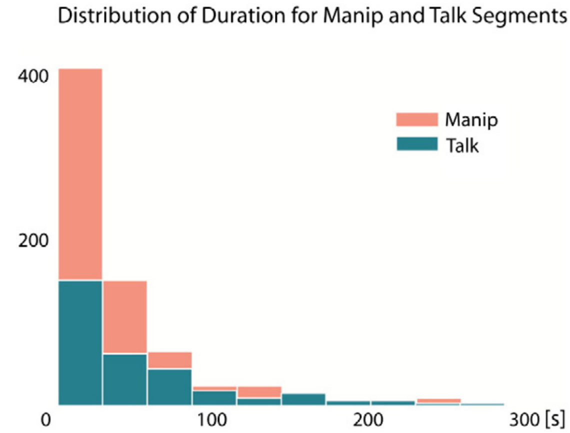

Fig. 1. Manip and Talk time segment histograms.

3.2. Models

Table 3 shows the significant predictors remaining in each of the four models after non-significant fixed effects and their corresponding random effects were removed. Details of each model are described in the paragraphs that follow.

3.3. Longitudinal control

The variables MinTTC and MedHW were not correlated, and the different models reflect that fact. For MinTTC, time was significant after adjusting for segment duration. As shown in Fig. 2, MinTTC was longest during Phone (mean = 3.64 s), followed by Pre-Phone (mean = 3.45 s), and shortest during Post-Phone (mean = 2.64 s). Post-hoc tests show that the difference in MinTTC during Phone was significantly longer than during Post-Phone ($t(78.3) = -2.44$, $p = 0.0169$).

In contrast, MedHW varied by age group, but not by task, after adjusting for segment duration. Younger drivers kept the shortest median headway (mean = 35.6 m), followed by middle-aged drivers (mean = 40.0 m), and older drivers (mean = 44.7 m); see Fig. 2. The differences between young drivers and each of the other age groups were significant (younger vs. middle-aged: $t(485) = 2.97$, $p = 0.0031$; younger vs. older: $t(517) = 3.43$, $p = 0.0007$).

In summary, (a) the older the drivers the farther they drove from the vehicle in front, independent of the phone task, and (b) during phone tasks, drivers experienced less–critical longitudinal threats (short time-to-collision) independent of the nature of the phone task and their age.

3.4. Lateral control

The lateral control measures MinTLC and MaxLO were moderately correlated in the dataset, but the best models for these two measures were not identical. For MinTLC, only task was a significant predictor (after adjusting for segment duration and the task-by-segment duration interaction). Manip had significantly greater MinTLC (mean = 1.23 s) than Talk (mean = 0.99 s); see Fig. 2.

For MaxLO, all three main effects of age group, task, and time were significant after adjusting for the effects of segment duration and the task-by-segment duration interaction. Older drivers had the greatest

Table 1
Correlation matrix for four dependent variables in the 3099 segments.

	MinTTC	MedHW	MinTLC	MaxLO
MinTTC	1.00	0.16	0.11	−0.14
MedHW		1.00	−0.05	−0.05
MinTLC			1.00	−0.40

Table 2
Percentage of available data for dependent variables.

	MinTTC	MedHW	MinTLC	MaxLO
Overall	50	70	78	100
Young	48	68	74	100
Middle-aged	53	73	82	100
Old	56	68	87	100
Manip	45	64	73	100
Talk	60	81	88	100
Phone	50	68	76	100
Pre-Phone	49	70	78	100
Post-Phone	51	70	79	100

MaxLO (mean = 1.24 m), followed by middle-aged drivers (mean = 1.13 m) and younger drivers (mean = 1.05 m; see Fig. 2). The differences between younger drivers and the other age groups were significant (younger vs. middle-aged: $t(103) = -2.30$, $p = 0.0236$; younger vs. older: $t(227) = -2.75$, $p = 0.0065$). MaxLO during Phone events was significantly smaller than during Pre-Phone or Post-Phone (Phone vs. Pre-Phone: $t(2837) = 3.57$, $p = 0.0004$; Phone vs. Post-Phone: $t(2838) = 4.21$, $p = 0.0004$). The variable MaxLO was significantly greater for Talk than Manip.

In summary, (a) the older the drivers the more likely they were to drive closer to the road shoulder; (b) while talking on a phone, drivers were also more likely to be closer to the road shoulder than while manipulating a phone; and (c) while talking on a phone, drivers experienced more critical lateral threats (short time-to-lane crossing) than while manipulating a phone.

4. Discussion

4.1. Older and middle-aged vs younger drivers

In accordance with previous studies arguing that younger generations are more likely than older generations to use a phone while driving (Brusque & Alauzet, 2008; Nelson et al., 2009), younger drivers in the IVBSS study engaged in more phone-related tasks than middle-aged and older drivers. The ratio of Manip to Talk tasks varied with age (3.1, 1.5, and 0.8 for younger, middle-aged, and older drivers, respectively). Thus, for older drivers, Talk was preferred over Manip, confirming the common hypothesis that older generations use mobile phone mainly for phone conversations—whereas younger generations use mobile phones for a wider variety of tasks, such as texting (Young & Lenné, 2010). In addition, elderly drivers may also initiate calls less often than younger drivers.

Both longitudinal and lateral control was affected by age. In fact, older and middle-aged drivers maintained significantly larger headway, as well as distance from the road center, than younger drivers. This result confirms the finding of previous studies that older drivers keep larger safety margins (e.g., Andrews & Westerman, 2012; Brouwer et al., 1991), for longitudinal and lateral margins, respectively). A possible explanation for the older group's larger safety margins relies on the interplay of individual perception of driving performance and risk. In general, older drivers are aware of their reduced ability to perceive and react to threats (Hancock et al., 2003; McPhee et al., 2004; Rogé & Pébayle, 2009) especially when distracted (Shinar et al., 2005); they may increase their safety margins accordingly (Young & Lenné, 2010). At the same time, younger drivers perceive risk differently than older drivers, taking higher risks—which may involve reducing safety margins (Cestac et al., 2011).

Interestingly, neither MinTLC nor MinTTC (indicators of lateral and longitudinal threat) were significantly different across age groups in our study. This suggests that even when younger drivers had a smaller safety margin, they could react fast enough to keep their MinTLC and MinTTC in the same range as middle-aged and older drivers. Compensatory behavior based on individual perception of risk and driving performance would also explain why the interaction between age and task was not significant in our analysis. In fact, younger drivers may have taken higher risks (Constantinou et al., 2012) than older drivers while using the phone because they judge themselves as being better at reacting while distracted by the phone (Brouwer et al., 1991).

4.2. Manip vs Talk phone task segments

Longitudinal control was not significantly different for Manip and Talk. This was not expected, since Manip requires longer times with eyes off-road than Talk (Fitch et al., 2013), and one might therefore expect Manip to exhibit lower longitudinal safety margins than Talk. One possible explanation is that drivers successfully predicted steady-traffic conditions before initiating a phone interaction (Tivesten & Dozza, 2015).

Manip and Talk influenced lateral control differently. During Talk, drivers exhibited shorter MinTLC and larger MaxLO, possibly because they drove closer to the edge of the road, whereas during Manip, drivers tended to stay more in the middle of the lane. This difference in behavior is consistent with the different glance strategies required for Talk and Manip (Victor & Dozza, 2011). Since Manip may require longer glances away from the road, a more centered position is safer. In contrast, during Talk, the drivers' eyes are generally on the roadway, thus driving closer to the curb may be safer even if it may result in lower MinTLC.

4.3. Pre-Phone and Post-Phone vs Phone segments

MinTTC was lower in Post-Phone than in Phone events. This result may be explained by drivers being likely to end phone calls when entering driving conditions with higher traffic density, where more attention to the longitudinal control of the vehicle is necessary.

Phone-related events exhibited lower MaxLO than both baseline events (Pre-Phone and Post-Phone). A possible explanation is that during the Phone task the driver engages in tighter lateral control, changing lanes less frequently, and possibly avoiding overtaking. This result is consistent with simulator studies that show that drivers look around less, follow less closely, and change lanes less often when talking on the cell phone.

4.4. Driver compensatory behavior

This study suggests that drivers may be aware of their skills (e.g., reaction times) and, when aging, adapt their driving accordingly to control for risk. This study also suggests that drivers regulate lateral control when using a phone, possibly in the effort to control for the increased risk posed by phone use. Several recent studies suggest that

Table 3
Significant predictors for each of four models.

		MinTTC	MedHW	MinTLC	MaxLO
Predictors	Age		$F(2499) = 8.53$, $p = 0.0002$		$F(2153) = 4.95$, $p = 0.0083$
	Task			$F(1194) = 32.4$, $p < 0.0001$	$F(1194) = 30.4$, $p < 0.0001$
	Time	$F(1,78.5) = 3.4$, $p = 0.0393$			$F(2,2837) = 10.3$, $p < 0.0001$
Covariates	Duration	$F(1604) = 25.2$, $p < 0.0001$	$F(1,87.9) = 9.6$, $p = 0.0027$	$F(1,51.3) = 183.0$, $p < 0.0001$	$F(1,63.9) = 231.8$, $p < 0.0001$
	Duration × Task			$F(1202) = 21.7$, $p < 0.0001$	$F(1,25.9) = 16.6$, $p = 0.0004$

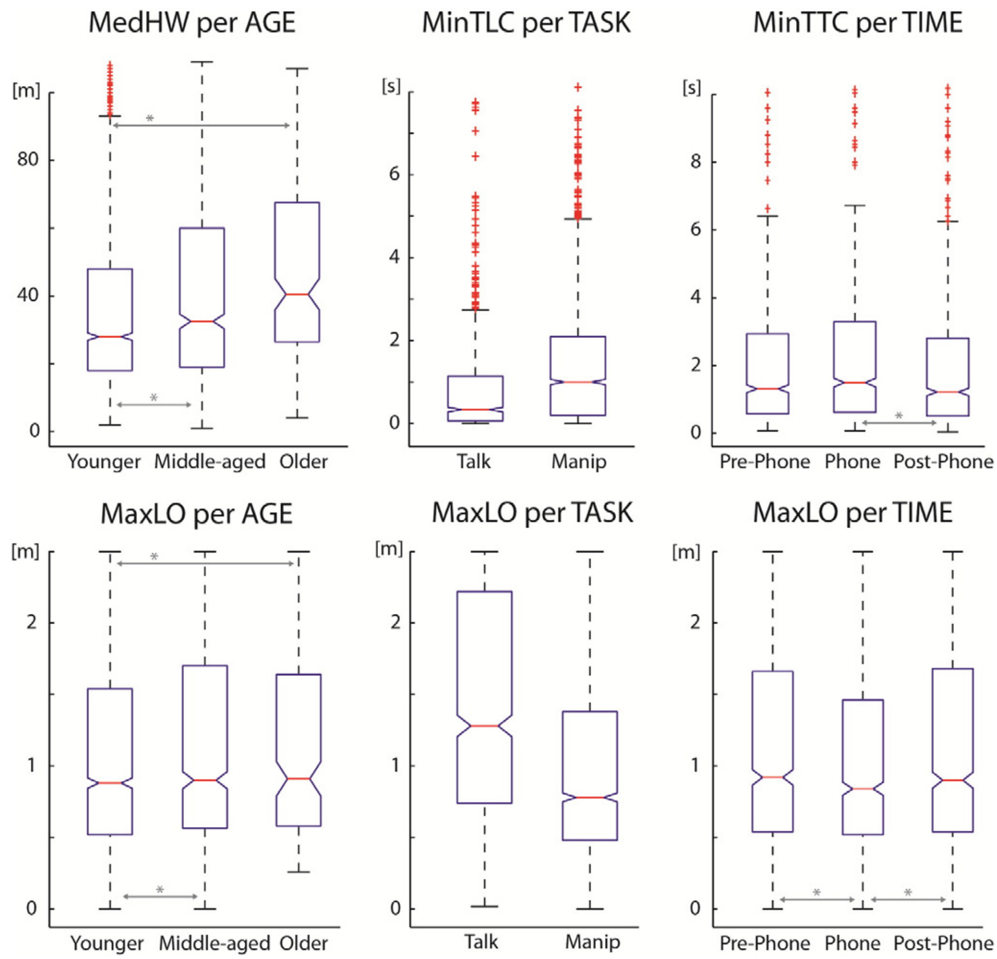

Fig. 2. Main statistically significant effects on lateral and longitudinal indicators. In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Notches indicate 95% confidence interval for the medians.

drivers indeed self-regulate (i.e., increase safety margins while attending to other tasks such as phone interaction; Zhou et al., 2012; IIHS-HLDI, 2014; Tivesten & Dozza, 2014; Young, 2014) to reduce risk. Thus, self-regulation may just be a specific instance of compensatory behavior and may be the key to reconciling controlled experiments and naturalistic observations as well as inspiring the development of highly acceptable countermeasures.

Controlled experiments may simply not give enough time or options for drivers to show their natural compensatory behavior leading to biased results that are not found in real traffic. Interestingly, some controlled experiments, such as Schömig and Metz (2012), show that, when drivers are allowed, they do self-regulate also in controlled environments, for instance by stopping the vehicle when they feel that the situation is not suitable for multi-tasking while driving.

Understanding for which drivers and in which situations self-regulation succeeds or fails may be the key for the development of highly acceptable countermeasures to traffic crashes. For instance, this knowledge can identify topics, target population, and timing for campaigns, training, and education. In addition, advanced driver assistance systems could be designed to boost the natural compensatory behavior of the driver instead of reprimanding the driver with warnings. Positive reinforcement of compensatory behavior might result in highly acceptable and largely adopted countermeasures to traffic crashes.

4.5. Limitations and future analyses

Limitations in this study arise from (a) the nature of the data, (b) the specific database, and (c) our analysis methodology. Naturalistic data are influenced by all possible environmental variables such as weather, traffic density, and road type, as well as by driver state and possible impairments. These confounders are hard to control and may have biased our analysis. The 108 drivers in the IVBSS dataset were volunteers and drove mostly in a specific geographical location (southeast Michigan), so our results may be biased by state-specific confounders, including laws and driver behavior. Coding of phone use depended on subjective evaluations and video data (Funkhouser & Sayer, 2011). The selection criteria, which strongly reduced the number of analyzed phone segments, may have also biased the sample and potentially excluded some specific driving scenarios.

Future studies may make use of larger datasets such as SHRP2 (Campbell, 2013) to validate and extend the results presented in this paper while overcoming its possible biases. The use of larger datasets could further assess (a) whether the relation between duration of phone interactions and risk is linear (just a consequence of exposure), (b) the possible interplay between self-regulation and the driving context, and (c) which driver's characteristics/styles affect compensatory behavior.

5. Conclusions

This study shows that drivers increase their safety margins as they age, as well as while using a phone, to possibly control for risk. Drivers also experienced more severe longitudinal threats just after phone use, suggesting that a driver may decide to end a phone interaction depending on the driving context. These findings may be explained in terms of compensatory behavior and self-regulation, both harder to measure in controlled experiments than in naturalistic studies.

Current advanced driving support systems rely on negative feedback (warning) to improve lateral and longitudinal control. A longitudinal/lateral support system inspired by compensatory behavior may increase headway/change lateral offset instead of warning a driver, resulting in a more natural and acceptable feedback for the driver. Finally, future studies should investigate which drivers are most skilled at self-regulating and in which contexts self-regulation fails.

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