CELL PHONES AND DRIVING PERFORMANCE: A META-ANALYSIS

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A meta-analysis was conducted to explore the costs associated with cell phone use while driving, using standardized measures of effect size along five dimensions (moderator variables) that were hypothesized to impact the costs associated with cell phone use. Sixteen studies (contributing a total of 37 analysis entries) met the appropriate conditions for the meta-analysis. Overall, there were clear costs to driving performance when drivers are engaged in cell phone conversations. However, investigation of moderator variables indicated that these costs were borne primarily by reaction time tasks, with far smaller costs associated with tracking (lane keeping) performance. Hands-free and hand-held phones revealed similar patterns of results, as did simulator versus field studies. Conversation tasks tended to show greater costs to performance than did information-processing tasks (e.g., word games). Finally, costs in driving performance were roughly equivalent whether the conversation was with a passenger or whether over a cell phone.

Over the past 10 years, there has been accelerated use of cellular or mobile phones—an increase that has been coupled with an acceleration of studies that have attempted to document the negative safety implications of their use while driving (e.g., Alm & Nilsson, 1994; McKnight & McKnight, 1993). However, at present, the issue of how much driving interference cell phone use produces is complicated by conflicting findings. For example, Brookhuis, de Vries, & de Waard (1991) showed that drivers exhibited *decreased* lane deviations while engaged in a cell phone task, whereas others have shown the opposite effect for tracking performance (e.g., Strayer & Johnston, 2001). Furthermore, some epidemiological studies highlight the very high safety record of cell phones in specialized uses (e.g., ONSTAR assistance calls; Young, 2001), and others raise safety concerns regarding more general use (Redelmeier & Tibshirani, 1997). Given such inconsistencies, we decided to integrate the collective wisdom of many of the empirically valid studies, through the technique of *meta-analysis* (Rosenthal, 1991).

Meta-analysis is a technique whereby the results of a number of studies exploring a hypothesis can be combined to provide a single estimate of the reliability and magnitude of the effect supporting (or refuting) that hypothesis. In the current case, the effect we measure is the degradation in driving performance when using a cell phone, compared with a single task, driving control condition. Meta-analysis also allows for the testing of more restricted hypotheses addressed by a subset of research reports. For example, we might wish to ask if the effect of cell phone use was the same on lane keeping performance as on hazard response, or whether the effect was the same for both hands-free and hand-held cellular phones. We refer to these as *moderating variables* that can modify the main effect of cell phone use.

In carrying out our meta-analysis, we identified five moderating variables that (a) we hypothesized might influence the costs of cell phone use on driving performance and (b) could be important in modeling the effect on the driver's attentional system. These are:

1. Measures of driving performance. Prior research has established that continuous perceptual-motor measures of lane keeping depend on separate attentional resources and are differentially affected by concurrent task demand than are discrete measures of hazard response (Horrey & Wickens, in review).
2. Hand-held versus hands-free. Some have argued that the primary source of interference for drivers using a cell phone is between the manual dexterity necessary to hold the phone and the manual steering activity—a source of interference that would be evident only in hand-held phones. Others have argued that the primary source of interference is cognitive, related to the information processing activities of listening and selecting vocal responses (e.g., Strayer & Johnston, 2001). Therefore, we consider interference separately in studies using hand-held versus those using hands-free phones.
3. Conversation versus information processing. There have been a number of studies that employ realistic conversation tasks (e.g., Strayer & Johnston, 2001), which may "engage" the driver in varying degrees, depending on their level of interest. In contrast, other researchers employ tasks that simulate the demands of conversation on different aspects of information processing (e.g., Alm & Nilsson, 1994). We have therefore contrasted studies that have used the two types of tasks to simulate cell phone usage.
4. In-vehicle versus remote conversation. It has been argued by some that a major source of distraction in cell phone use is the inability of the non-driving speaker to be aware of the momentary demands on the driver, and hence, the inability to modulate conversation when the driving demands increase. This inability does not characterize the passenger in the vehicle, who may be carrying out the same conversation (e.g., Gugerty, Rando, Rakauskas, Brooks, & Olson, 2003). Hence we contrasted studies that used the two classes of conversation.
5. Simulator versus field studies. Given the frequent citation of cell phone costs in the context of simulator studies, we were interested in whether these findings were consistent with real world in-vehicle field trials, more characteristic of the environments from which epidemiological accident data are drawn (e.g., Redelmeier & Tibshirani, 1997; Young, 2001).

METHODS

Study Selection

A comprehensive search of the literature returned 42 different papers on cell phones and driving, through online databases (e.g., PSYC INFO), backwards referencing, and web searches. These included journal articles, conference proceedings, and technical reports. From this set, we identified 21 studies that had empirical findings concerning the impact of cell phones on tracking performance, vehicle control, or response time to a non-cell phone event (e.g., roadside hazard), which represented the variables we were most interested in. Also, because we were interested in the conversational aspects of cell phone use, we did not include studies that examined driving performance while the driver was dialing or manipulating the cell phone in some way. We also note that, although we do not include epidemiological studies involving collision statistics or studies focusing on other measures such as workload, it is not our intention to imply that these findings are not important or relevant.

We further reduced the set of studies by identifying those studies that met the criteria for the meta-analyses. For example, meta-analyses require that all findings be presented in terms of single degree-of-freedom (df) main effects, most especially in cases where the raw data are unavailable. Furthermore, we required that all the studies include a common comparison of cell phone use while driving against single-task baseline conditions (e.g., driving alone). As such, studies that did not meet these criteria were dropped from this analysis (see Horrey & Wickens, 2004, for more details).

From the original set of papers, we were left with sixteen experiments, which contributed to the current meta-analysis (see Table 1). In some cases, studies had several relevant conditions, which allowed us to increase the overall number of analysis entries (up to 37 overall). For example, some studies examined both hand-held and hands-free cell phones—conditions that were included in the meta-analysis as separate entries[1].

Variable Coding

Each of the selected studies was coded along the five moderator variables. Specifically, we indicated whether the study measured tracking performance (e.g., absolute error or variability in tracking) or response time (i.e., involved a speeded response to some stimuli, whether a road hazard or an artificial stimulus presented in the traffic environment). Second, we coded whether a particular study employed a hands-free or a hand-held cell phone for the conversation task. Third, we categorized the type of phone task that participants performed, that is, whether the task involved a conversation (typically characterized by a free discussion of topics-of-interest or autobiographical information) or an information-processing task (e.g., mental arithmetic, word generation games). Next, we specified those studies that utilized remote (i.e., over a cell phone) conversations and those that incorporated in-vehicle (i.e., passenger) conversations and, finally, those that used simulators (whether low or high fidelity) versus those employing actual field trials.

Meta-Analysis

For the meta-analysis, we converted statistical results into effect sizes and combined these values in following procedures described by Rosenthal (1991) and Rosenthal and Dimatteo (2001). Effect sizes are advantageous because they focus on how large a particular effect is (as opposed to whether or not it differs from zero) and, when coupled with confidence intervals, they offer estimates for the upper and lower limits of the true effect size in the population.

Effect size, based on the product moment correlation (r), was calculated using the test statistics (t- or F-values) reported in each study (see Equation 1). We employed r as a measure of effect size because it has a number of advantages over other measures (e.g., Cohen's d, Hedges' g; see Rosenthal, 1991, for details).

$$r_{ES} = \sqrt{\frac{t^2}{t^2 + df}} = \sqrt{\frac{F}{F + df_{error}}} \quad (1)$$

In situations where the authors indicated no difference between the conditions of interest but failed to provide any statistical details (e.g., $F < 1$), a conservative effect size of zero was assumed for the meta-analysis (see Rosenthal & Dimatteo, 2001).

Following the calculation of the effect size (r_{ES}) for each study, we coded the findings to denote costs or gains in driving performance with the concurrent cell phone task. In the first case, effect sizes were assigned positive values given that this pattern was consistent with the hypotheses (i.e., predicted costs to performance). In cases where the pattern of results was opposite predictions (i.e., gains in performance in dual-task situations), effect sizes were assigned negative values.

In order to combine the effect sizes from multiple studies, we first normalize our individual effect sizes by converting the r_{ES} scores to z-scores using Fisher's r-to-z transformation. Next, the mean of these transformed scores was calculated and then converted back into an r-value. Finally, we estimated the 95% confidence interval, to determine whether the combined effect sizes differ significantly from zero (that is, do not include zero in the interval), following Equation 2.

$$CI_{95\%} = \overline{Z_r} \pm t_{(.05)} S / \sqrt{k} \quad (2)$$

where $\overline{Z_r}$ is the mean of the transformed r_{ES} values, $t_{(.05)}$ is the appropriate t value for the 0.05 probability level, S is the standard deviation of the transformed r_{ES} values, and k is the number of studies included in the sample.

[1] Because some studies are contributing multiple entries in certain aspects of the meta-analysis, the treatment of such non-independent results as independent may draw some criticism. This may be the case for significance testing, however, not in dealing with estimates of effect size, as we are dealing with here (see Rosenthal, 1991, for a detailed discussion).

Study	Phone Type	Task Type	Location	Measure	Study Type
Alm, H. & Nilsson, L. (1994). Changes in driver behaviour as a function of handsfree mobile phones—A simulator study. *Accident Analysis and Prevention, 26*(4), 441-451.	Hands-Free	Information Processing	Remote	Tracking	Sim
Alm, H. & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis and Prevention, 27*(5), 707-715.	Hands-Free	Information Processing	Remote	Tracking, RT	Sim
Brookhuis, K.A., de Vries, G., & de Waard, D. (1991). The effects of mobile telephoning on driving performance. *Accident Analysis and Prevention, 23*(4), 309-316.	Hands-Free, Hand-Held	Information Processing	Remote	Tracking, RT	Field
Consiglio W., Driscoll, P., Witte, M., & Berg, W.P. (2003). Effect of cellular telephone conversations and other potential interference on reaction time in a braking response. *Accident Analysis and Prevention, 35*, 495-500.	Hands-Free, Hand-Held	Conversation	Remote, In-Vehicle	RT	Sim
Gugerty, L., Rando, C., Rakauskas, M., Brooks, J., & Olson, H. (2003). Differences in remote versus in-person communications while performing a driving task. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting* (pp. 1855-1859). Santa Monica, CA: HFES.	Hands-Free	Information Processing	Remote, In-Vehicle	RT	Sim
Irwin, M., Fitzgerald, C., & Berg, W.P. (2000). Effect of the intensity of wireless telephone conversations on reaction time in a braking response. *Perceptual and Motor Skills, 90*, 1130-1134.	Hand-Held	Conversation	Remote	RT	Sim
Laberge, J., Scialfa, C., White, C., & Caird, J. (2004). The effect of passenger and cellular phone conversations on driver distraction. *83rd Annual Meeting of the Transportation Research Board*. Washington, DC: National Academy of Sciences.	Hands-Free	Information Processing	Remote, In-Vehicle	RT	Sim
Lamble, D., Kauranen, T., Laakso, M., & Summala, H. (1999). Cognitive load and detection thresholds in car following situations: Safety implications for using mobile (cellular) telephones while driving. *Accident Analysis and Prevention, 31*, 617-623.	Hands-Free, Hand-Held	Information Processing	In-Vehicle	RT	Field
Parkes, A.M. & Hooijmeijer, V. (2001). Driver situation awareness and carphone use. *Proceedings of the 1st Human-Centered Transportation Simulation Conference* (ISSN 1538-3288). Iowa City, IO: University of Iowa.	Hands-Free	Information Processing	Remote	Tracking, RT	Sim
Patten, C.J.D., Kircher, A., Östlund, J., & Nilsson, L. (in press). Using mobile telephones: Cognitive workload and attention resource allocation. *Accident Analysis and Prevention*.	Hands-Free, Hand-Held	Information Processing	Remote	RT	Field
Rakauskas, M., Gugerty, L. & Ward, N.J. (in review). Effects of cell phone conversations on driving performance with naturalistic conversations.	Hands-Free	Conversation	Remote	Tracking, RT	Sim
Strayer, D.L. & Drews, F.A. (2003). Effects of cell phone conversations on younger and older drivers. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting* (pp. 1860-1864). Santa Monica, CA: HFES.	Hands-Free	Conversation	Remote	RT	Sim
Strayer, D.L., Drews, F.A. & Johnston, W.A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied, 9*(1), 23-32.	Hands-Free	Information Processing, Conversation	Remote	RT	Sim
Strayer, D.L., Drews, F.A., Albert, R.W., & Johnston, W.A. (2002). Why do cell phone conversations interfere with driving? *81st Annual Meeting of the Transportation Research Board*. Washington, DC: National Academy of Sciences.	Hands-Free, Hand-Held	Conversation	Remote	RT	Sim
Strayer, D.L. & Johnston, W.A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular phone. *Psychological Science, 12*(6), 462-466.	Hands-Free, Hand-Held	Information Processing, Conversation	Remote	Tracking, RT	Sim
Waugh, J.D., Glumm, M.M., Kilduff, P.W., Tauson, R.A., Smyth, C.C., & Pillalamarri, R.S. (2000). Cognitive workload while driving and talking on a cellular phone or to a passenger. *Proceedings of the IEA 2000/HFES 2000 Congress* (pp. 6:276-6:279). Santa Monica, CA: HFES.	Hand-Held	Information Processing	Remote, In-Vehicle	Tracking	Field

Table 1. List of studies contributing to the meta-analysis and some of their attributes.

RESULTS

The results from the meta-analysis are shown in Table 2. When we examine all of the studies collectively (without factoring in moderator variables), we find that there is a large, significant cost of cell phone use on driving performance (see row **1**, Table 2). We proceeded to break down the set of studies following the moderator variables outlined previously. (When examining the interactive effects of multiple moderator variables, we did not analyze all possible combinations of variables, instead focused on those combinations that were of greatest interest to us.)

		Number of Entries	Combined Effect Size (r)	95% Confidence Interval
1) Overall	-	37	0.50	(0.29, 0.60)
2) Measure	**a**) RT	26	0.60	(0.49, 0.69)
	b) Tracking	11	**0.22**	**(-0.10, 0.49)**
3) Phone Type	**a**) Hands Free	24	0.47	(0.33, 0.59)
	b) Hand Held	13	0.55	(0.31, 0.73)
4) Task Type	**a**) Conversation	15	0.64	(0.51, 0.74)
	b) Info Process	22	0.39	(0.22, 0.55)
5) Location	**a**) Remote	31	0.49	(0.32, 0.57)
	b) In-Vehicle	6	0.55	(0.22, 0.77)
6) Study Type	**a**) Simulator	25	0.55	(0.43, 0.63)
	b) Field Test	12	0.42	(0.07, 0.68)

Table 2. Summary table for the meta-analysis, including the examination of moderator variables. (Bold results indicate non-significant findings, i.e., confidence interval includes zero.)

As shown in row **2** of Table 2, we broke down the overall set of studies into those that examined driving performance in terms of response time (RT) to a road event or stimuli or in terms of lane keeping or tracking performance. For those studies examining RT (**2a**), the costs to driving performance were still significant (with a large effect size, which translated to approximately 130 msec in costs). However, for those studies that examined decrements in tracking performance or lane keeping (**2b**), the effect size was substantially smaller and non-significantly different from zero (that is, the 95% CI included zero).

An examination of the overall impact of phone type on overall driving performance (hands-free, **3a**; hand-held, **3b**) showed significant costs that were comparable for both types of phones.

We broke down the overall set of studies by those employing conversation tasks and those using information-processing tasks (**4**). In general, when a conversation task is employed there are high costs to driving performance (**4a**), more so than for information processing tasks (**4b**), which lies more than the 95% confidence interval below conversation. However, both costs were still significant.

In comparison **5**, we note that the distinction of in-vehicle or remote conversations does not appear to have a differential impact on the costs in driving performance. That is, the costs associated with a phone conversation versus a passenger conversation are roughly equivalent. Finally, the costs observed in simulator and field studies was similar (**6**), though we note there were more variable findings for the field work.

DISCUSSION

From the current meta-analysis, we note several important findings. First, there are definite costs associated with cell phone use while driving, however these costs appear to be manifested primarily in measures of response time to critical road hazards or stimuli. In contrast, the costs associated with lane keeping or tracking performance are much smaller (and, in this case, non-significant). Horrey and Wickens (in review) suggest that these tasks (e.g., lane keeping and hazard response) depend on separate resources (ambient and focal vision, respectively) and may be differentially impacted by cell phone conversations. Furthermore, lane keeping may be a skill that is relatively automatic, requiring fewer overall resources to maintain performance (in addition to being supported by ambient vision). In contrast, responding to road events or stimuli may less automated because drivers must, not only detect critical objects, but also select an appropriate course of action or response to them. The interference derived from cell phone conversations may manifest itself at these stages of processing (i.e., decision making, response selection). We note that, while the magnitude of the reaction time effect was relatively small (an average delay of 130 ms), this represents a mean value, around which there is considerable variance. Accidents are often caused by "worst case" performers (Wickens, 2001), at the tail end of the distribution, where reaction time delay can be expected to be considerably longer.

Second, the meta-analysis suggests that costs in driving performance are roughly equivalent across hands-free and hand-held phones, suggesting that the larger part of these costs is due to the cognitive aspects of conversation and not the manual aspects of holding the phone. We note, however, that this does not discount the possibility that the costs associated with hand-held phones could exacerbated in situations requiring significant amounts of manual steering inputs, in particular, those costs incurred during intersection turns.

Third, conversation tasks, in general, showed greater costs in driving performance than did information processing tasks. This may be due to the greater "engagement" associated with actual conversations. That is, information-processing tasks, although they involve perceptual resources and working memory, might not share the same degree of engagement, as do conversations. We speculate that the costs of engagement may be more pronounced when the conversation is intense[2], though there was insufficient data along this dimension (across studies) for the purposes of meta-analysis. We also note that intense conversations are difficult to replicate in a controlled experimental setting.

From our analyses, in-vehicle, passenger conversations were just as costly to driving performance as were remote (cell

[2] Some researchers have defined an intense conversation as one that is difficult or challenging (e.g., problem-solving exercises; McKnight & McKnight, 1993). However, we differentiate here between phone tasks that may be considered difficult and those that may be emotionally loaded or heated (as we consider "intense").

phone) conversations. This suggests that passengers, at least in those studies and with the methodologies explored here, did not moderate their conversation in such a way as to alleviate the costs (compared to remote conversers).

Finally, the costs to driving performance exhibited in simulator studies were similar and were less variable to those found for field trials, suggesting that the former may be useful in generalizing to real-world driving situations.

Although the technique of meta-analysis lacks the experimental control from a single experiment, it does afford investigators a useful tool for integrating the collective contributions of multiple studies. As noted by Hall and Rosenthal (1995), there is no single way to perform a meta-analysis. In our current analysis, we elected to focus on the impact of cell phone use on lane keeping (tracking) and event response time, as these relate to the driving tasks of vehicle control and hazard awareness. We do note that these two measures represent logical precursors to the less frequently observed loss-of-control and collision events, respectively. Other important measures, such as workload and collision frequency, may also provide the foundation for other meta-analyses. Furthermore, we focused on the conversational aspect of cell phone use. Others may tap the interference derived from the physical manipulation of a cell phone (e.g., dialing) on steering behavior.

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