

Cognitive Distraction While Driving: A Critical Review of Definitions and Prevalence in Crashes

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ABSTRACT

There is little agreement in the field of driving safety as to how to define cognitive distraction, much less how to measure it. Without a definition and metric, it is impossible to make scientific and engineering progress on determining the extent to which cognitive distraction causes crashes, and ways to mitigate it if it does. We show here that different studies are inconsistent in their definitions of cognitive distraction. For example, some definitions do not include cellular conversation, while others do. Some definitions confound cognitive distraction with visual distraction, or cognitive distraction with cognitive workload. Other studies define cognitive distraction in terms of a state of the driver, and others in terms of tasks that may distract the driver. It is little wonder that some studies find that cognitive distraction is a negligible factor in causing crashes, while others assert that cognitive distraction causes more crashes than drunk driving. Perhaps the largest problem however is that the definitions typically refer to distraction as a reduction of attention, but never define attention. It is recommended that a new definition of cognitive distraction be created, based on observational data of actual rather than simulated driving. This definition should have associated with it a clear metric for assessing the amount of cognitive distraction for a wide range of tasks, involving different sensory and motor modalities (visual-manual, auditory-vocal, tactile, etc.) A new foundation, grounded in on-road driving data and the experimental study of attention within cognitive neuroscience, may improve the speed at which new and effective countermeasures are developed, crashes are reduced, and driving safety is improved for all.

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INTRODUCTION

"Everyone knows what attention is."

1. William James (1890) [1]

"Keep your mind on the drive instead of the dials with the only radio custom built for your 1939 Buick."

2. General Motors Corporation (1938) [2]

"Many people automatically presume that it is possible to 'still the mind' - not think about anything; have no specific conscious thoughts - for minutes if not hours. But a noted Japanese Zen priest once astounded his novice disciples by stating that the longest he had ever been able to keep his mind blank was one second."

3. De Mente (2000) [3]

The current paper is concerned with a critical review of existing definitions, metrics, and models for cognitive distraction, and how prevalent cognitive distraction is before a crash. In a companion paper [4] we attempt a new scientific definition of cognitive distraction while driving based on its relationship to event detection and response. The overall goal is to improve the fundamental understanding of the cognitive

processes underlying human-vehicle integration during driving (of which attentional processes are key), to reduce crashes. The questions answered in the current study are:

1. What are the limitations of current "cognitive distraction" definitions during driving?
2. What are the limitations of current metrics and models for "cognitive distraction" effects while driving?
3. Why are there wide-ranging estimates of the prevalence of cognitive distraction preceding vehicle crashes?

1. LIMITATIONS OF CURRENT "COGNITIVE DISTRACTION" DEFINITIONS

Most definitions of cognitive distraction in the driving distraction literature categorize cognitive distraction as one type of driver distraction (e.g., "mind off the drive"). Other types of driver distraction are termed "visual" (e.g., "eyes off the road") or "manual" (e.g., "hands off the wheel").

However, beyond the minimal level of agreement that cognitive distraction is one form of driver distraction, there are discrepancies its definition. These discrepancies although often subtle, lead to differences in which secondary tasks while driving are or are not within the scope of cognitive distraction, and what metrics should be used to measure them. These discrepancies in turn have safety consequences, because if a task is not tested for “cognitive distraction” because it is excluded by the definition, then the crash risk potentially associated with that cognitive distraction may be missed (“not defined so did not see”).

A sample of cognitive distraction definitions in the existing driver performance literature is given in [Appendix A](#). (There are also definitions of cognitive distraction in the attention, psychology, and cognitive neuroscience literature, but these are not yet specifically applied to driving.) These definitions can be separated into classes or categories in many different ways. Because of the wide interest in the topic of cell phones and driving, and the frequent association of cell phone conversations (including both hand-held and hands-free conversations) while driving with “cognitive distraction,” we here use the task of cellular conversation to illustrate the differences between the cognitive distraction definitions (even though there are many other ways to categorize the definitions). Thus, the definitions in [Appendix A](#) are grouped according to whether they include cellular conversations or not within their scope. (Note that the task of cell phone conversations is not pre-designated as a distraction and then used to judge the definitions; it is simply used to illustrate the underlying assumptions in the different definitions.) The sorting variable of “cellular conversation” is chosen simply for illustrative purposes; other sorting variables give to similar issues. Four of the overall major problems with the definitions in [Appendix A](#) are listed in Sections 1.1, 1.2, 1.3, 1.4, most of which apply equally well to the broader category of definitions of “driver distraction” [5,6].

1.1. ATTENTION UNDEFINED

The definitions in [Appendix A](#) mostly define “cognitive distraction” in terms of a withdrawal or diversion of attention, but they do not define attention. They rely upon each person's every day or informal understanding of “attention,” as per the quote by the pioneering American psychologist William James [1,7] at the start of this paper that, “Everyone knows what attention is.” The difficulty is that a personal understanding of “attention” may differ from individual to individual. “Introspection” has not been accepted as a valid method of experimental psychology since James' time in the nineteenth century. Relying upon each person's private understanding of the term “attention,” is not suitable grounds for scientific advancement, and may even hinder it.

Relying upon simple dictionary definitions (which use other words instead of scientific data to define things) gives rise to similar problems. It is not clear how metaphorical or figurative definitions of cognitive distraction in terms of other

undefined words or concepts will lead to technical advances in understanding cognitive distraction. Regan et al. [6, p. 172] cite the few definitions of “driver inattention” that exist in the driving literature and crash studies (which they note vary in meaning) before defining driver distraction using a dictionary. An interdisciplinary integration between the safety and human factors engineering approaches to driver performance, and the fields of cognitive psychology and cognitive neuroscience, may provide a new foundation to define cognitive distraction and attention - in a way that leads naturally to being able to measure cognitive distraction in driving and thus improves driving safety.

1.2. CONFUSION OF DRIVER STATE WITH DRIVER ACTIVITY

The definitions in [Appendix A](#) use the term “cognitive distraction” in incompatible and contradictory meanings. The first meaning refers to a driver *activity* - things external to the driver's mind, which may trigger the driver's thoughts to go “off the drive.” For example, “Conversation while driving is a cognitive distraction.” The term “cognitive distraction” as used in such definitions refers to the conversation itself, not the state of the driver. This first sense attempts to answer the question, “What activities are a ‘cognitive distraction’ for the driver?”

The second meaning refers to the driver *state* rather than the activity that distracts the driver. This meaning attempts to define the mental state of the driver when they are cognitively distracted. An example would be, “Cognitive distraction occurs when attention is not focused on the primary driving task.” Definitions in this class refer to the state of the driver, not the activity. This second sense attempts to answer the question, “What happens internally in the driver's mind (or brain) when they are cognitively distracted?”

These are two completely different meanings for the term “cognitive distraction.” This distinction is not trivial - the different meanings lead to practical consequences for deciding which metrics can best assess cognitive distraction and estimate its relative crash risk. Even the design of experiments intended to investigate and assess cognitive distraction will be influenced by which meaning is adopted. The definitions in [Appendix A](#) are labeled as “driver activity” or “driver state” to indicate which meaning they appear to be defining, so the reader can better understand the distinction.

1.3. OPERATIONAL DEFINITIONS LEAD TO INCONSISTENCIES

Many studies that claim to be investigating cognitive distraction never explicitly define it. Instead, they just list tasks or behaviors that they record as “cognitive distraction,” in observational terms (see [Appendix A](#), Section 1.4). They do not justify why they included those tasks as cognitive - they just make implicit assumptions that they are, and hope others agree. These are known as “operational” definitions of cognitive distraction. Even though the definitions are not

explicit, operational definitions necessarily contain an “implicit” or unstated definition. The various investigators who wrote the reports or journal articles could not have conducted the research or written up and classified the tasks as they did without an implicit definition. Because “operational definitions” are not within the context of an explicit theory or model, they often subtly change from one section to another in a single report, or from one report to another, even those describing the same data set. If different investigators use different observational data sets and have only operational definitions, it is almost impossible to compare results across studies. This lack of a clear theory or model of cognitive or driver distraction can give rise to inconsistent or even contradictory classifications of tasks and confusing taxonomies, leaving it uncertain as to what the prevalence and relative risk of “cognitive distraction” really is [6].

1.4. “LIMITED CAPACITY” SINGLE BOTTLENECK MODELS MAY BE TOO LIMITED

Almost all the cognitive distraction definitions in [Appendix A](#) contain an underlying often-implicit model of a “limited capacity” in a single central “channel” - with an assumption that exceeding some limit leads to a reduction in performance. There are four problems with using the model of a single limited capacity channel as part of the definition for cognitive distraction.

1. Little independent evidence is presented in support of this concept, other than that it is useful heuristic for the investigator to explain the data.
2. A single bottleneck model implicitly assumes that less “cognitive distraction” is always better - that optimal driving performance occurs with zero cognitive distraction. Driving itself is a highly multi-tasking activity for the brain, engaging perceptual, cognitive, motor, and many other brain functions. The driver however cannot focus exclusively on driving, because it is difficult or impossible to inhibit extraneous thoughts completely. The brain is always active - there is no “zero state” of brain activation (like there is for alcohol in the blood or eyes-off-road time), and no “zero” state for extraneous thoughts (as per the quote from the Zen master at the beginning of this paper [3] that the mind cannot be blank for more than one second). Indeed, focusing all thought exclusively on driving could lead to monotony and fatigue, reducing driver performance. The Yerkes-Dodson law [8] indicates that there is an optimum level of arousal at which performance peaks - too little or too much arousal gives rise to poor performance. Although driver workload, attention, or distraction are not the same as arousal or brain activity *per se*, there may be a similar optimum level for cognitive workload - too little cognitive workload may lead to a low arousal state with reduced vigilance. A moderate cognitive workload may improve arousal and performance. With too high a workload,

inhibitory processes in the brain play an important role in limiting the “amount” and “extent” of cognitive workload and distraction to a more optimum level for the driver. The way in which brain activity and cognitive workload interact with cognitive distraction may thus be considerably more complex than a simple “limited attention” bottleneck model.

3. A single bottleneck model is not consistent with cognitive neuroscience research of attentional networks in the brain, which indicate that there are three types of attentional networks as per Posner and colleagues [9, 10]. (Other investigators say there are fewer or more types of attention, or categorize them in different ways) However, the three network view probably has the most validation in the literature and provides a reasonable framework for quantitative studies of distraction.

4. Performance is multivariate in nature (Angell et al. [11]), with at least two separate underlying dimensions of driver distraction (Young [4], Young and Angell [12]). It is not clear how a single bottleneck model can affect both dimensions.

In sum, the problem of “cognitive distraction” (and driver distraction in general) is more complicated than a simple “limited capacity” bottleneck model. Modern science continues to reveal the function and operation of the underlying brain systems - and they are certainly not simple. Certainly not as simple as having a single central bottleneck - but it is also not the case that a driver can parallel process and attend to unlimited amounts of information. These complexities and subtleties mean that a scientifically grounded theoretical basis for a definition of cognitive distraction is becoming more important.

2. LIMITATIONS OF CURRENT METRICS AND MODELS FOR COGNITIVE DISTRACTION

2.1. “COGNITIVE TUNNELING”

“Cognitive tunneling” is conjectured to be a top-down attentional phenomenon that affects the ability of the visual system to detect and respond quickly to events in the periphery of the visual field, creating “tunnel vision.” The peripheral field is hypothesized to lose its relative sensitivity to stimuli in comparison to the central field, and so the driver now sees things in the periphery relatively less well than without cognitive tunneling, as if the driver perceived the world through a “tunnel” (Fig. 1) [13].



Figure 1. Illustration of concept of "cognitive tunneling" while driving [13].

This phenomenon is considered to occur beyond the fact that peripheral vision has far less acuity than central vision, due to the concentration of cone receptors in the fovea of the eye, within a central visual angle of only a few degrees. In addition, "cognitive tunneling" is conjectured to occur even if the driver remains fixated on the center of the roadway, and so it has unrelated to eye movements.

Some investigators propose "cognitive tunneling" as the underlying model or mechanism for "cognitive distraction." Therefore, metrics designed to measure peripheral event detection capabilities have been proposed as metrics for cognitive distraction. One of these is the Peripheral Detection Task (PDT), which measures the reaction time and miss rate for a small light stimulus placed in the periphery of the visual field [14]. Another is the Useful-Field-of-View (UFOV[®]) test where small symbols are placed in the periphery of the visual field and the observer must correctly identify them as rapidly as possible. The investigators who developed these metrics often refer to "cognitive tunneling" as the underlying mechanisms to explain their results. Many other driver distraction studies use the term "cognitive tunneling" or a "narrowing" of the "useful field of view" to explain their cognitive distraction results. A Google Scholar search for a conjunction of the three words "cognitive," "tunneling," and "driving" turned up 14,600 citations at the time of writing of the present paper.

There is no question that the UFOV[®] and the PDT have contributed to improving driver safety. The UFOV[®] test is correlated retrospectively or prospectively with a driver's crash record for example [15]. Its relation to many of the key major factors that affect driving performance (such as aging) is well established. However, the term "cognitive tunneling" as it has been widely used in driving research does not necessarily arise from a specific loss of sensitivity in the periphery of the visual field, as is often assumed in these studies. Later studies have shown that "cognitive tunneling" is not a specific loss of detectability (measured with miss

rates and response times) in peripheral vs. central vision. The original Peripheral Detection Task (PDT) used a peripheral light or lights, and found increased response times (RTs) to such lights with increases in cognitive load [16]. However, later studies have shown increased RT effects with a central light as much as with a peripheral light (Engstrom and Mardh [17]; Victor et al. [18]; Merat et al. [19]), or even with a tactile stimulus (Victor et al. [18]). These later PDT results showing no difference between central and peripheral lights are consistent with Young and Angell [12], who found that response times were similar for a central and peripheral light administered at different times during the same task, at least for the two major dimensions of driver performance. (There was a difference between central and peripheral response times only in a weak third component, less than 5% of total variation.) These later PDT studies agree that non-localized distractions that lead to a reduction of top-down attentional facilitation (the "spotlight" of attention) affect the entire retina, not just the periphery. Hence, the explanation of so-called "cognitive tunneling" may not really be a specific reduction of sensitivity of the periphery, but rather a reduced sensitivity in the entire visual field.

However, how can a reduction in overall responsiveness to visual stimuli lead to apparent "cognitive tunneling"? Fig. 2 illustrates one explanation. The taller blue curve peaking at "1" represents a (hypothetical) response profile for a driver who is fully alert with orienting attention on the road scene in the forward position (angle 0 in the figure). The exact shape of the blue curve is immaterial; all that is required is a decline in responsiveness away from the center of gaze (such as the reduced responsiveness that is known to occur as a visual stimulus moves away from the fovea or fixation point).

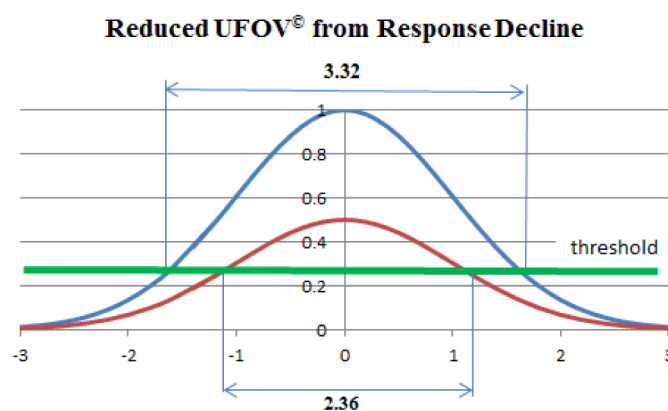


Figure 2. Demonstration how apparent "useful field of view" can change with an overall decline in responsiveness to visual stimuli. The horizontal axis is the retinal distance (in arbitrary units) away from the fixation point at zero. The vertical axis is responsiveness, measured in arbitrary units.

Assume the driver's threshold for responding to an object is given by the green horizontal line at 25% of the peak height of the large blue curve. If the blue curve is above the

green line, assume the drivers can respond to the stimulus, otherwise not. The “useful field of view” would then be the distance between the two points where the blue curve intersects the green line to the left and right of the center of gaze. The field size is here measured at 3.32 angular units (see distance marker at top of Fig. 2).

Now assume that the “spotlight” of orienting attention is diverted away from the fixation point by a stimulus in some region of the visual field that is more than three units away from the fixation point (location 0 in Fig. 2). Then as shown by Posner and colleagues [9,10] and others, there is a decline in responsiveness for the now unattended region. The smaller red curve represents an (arbitrary) reduction in responsiveness by 50% compared to the blue curve. The intersection of the smaller red curve with the green threshold line is now only 2.36 angular units (see distance marker at bottom of Fig. 2). The reduction in overall responsiveness has now shrunk the apparent UFOV around the fixed point from 3.32 to 2.26 angular units, or 29%.

Assume that instead of a visual stimulus, some other event occurs which activates a central orienting attentional network. Examples are: an auditory stimulus which is either non-localized, or localized to a region away from the fixation point; or, an auditory-vocal task like counting backwards by 7's, or verbally repeating the digits one or two back (the “n-back” task) while listening to a sequence of digits. These tasks would be expected to cause a similar reduction in facilitation from a central attentional network or networks, causing a decline in responsiveness to the smaller (red) curve in Fig. 2.

Note that in this example the apparent narrowing of the field of view arises from a lowering of responsiveness over the visual field, not just the periphery. The relative responsiveness of the different regions of the visual field, such as peripheral vs. central regions, does not change - all responses are reduced by 50%. This explanation may be more plausible for the declines in the UFOV[®] or “cognitive tunneling” than a mechanism that differentially affects the responsiveness of peripheral more than central areas. Note that the overall responsiveness decline need not be a simple decline in luminance or contrast responsiveness [20]. It may instead be a loss of responsiveness for moving or flashing stimuli [21,22]. The same cortical neurons in the visual striate cortex that respond to stationary briefly flashed stimuli (as are used in the UFOV[®] test or PDT test), also respond to moving stimuli [23,24].

2.2. CHANGE AND INATTENTIONAL BLINDNESS

A recent review [25] defines *change blindness* as “the surprising failure to detect a substantial visual change.” (This definition is unfortunately subjective because it requires a judgment of surprise.) *Inattention blindness* is defined [25] as “a failure to notice an unexpected, but fully-visible item when attention is diverted to other aspects of a display.”

Many interesting experiments and demonstrations of change and inattention blindness have been done in laboratory settings or sometimes even in real-world settings. Unfortunately, none of these experiments has explored these phenomena in actual on-road driving on a closed track or open road. Generalization to real-world driving from these experiments is therefore speculative. Change and attentional “blindness” phenomena may be related to some of the missed events in real-world driving, but the connections have not yet been experimentally made, nor has any relevant data been collected in actual rather than simulated driving. Therefore, it has not yet been experimentally demonstrated that such phenomena occur in a rich natural scene with all the visual cues that cannot be realized on a flat simulator or computer display. This phenomenon may depend on suppression of movement and luminance cues; thus, it may not generalize to real world driving in a substantial manner.

Indeed, the conditions for “change blindness” occur naturally all the time while driving, with or without secondary tasks. Every time a person blinks, their eyes are “off the road” for about a tenth of a second. A change in the visual scene that occurs during the blink technically meets the conditions for “change blindness” of having a blanking interval during which a visual change occurs. Alternatively, every time drivers make a saccade of any kind, they are getting the equivalent of a flashed blanking image equivalent to those used in change blindness paradigms in the laboratory. Thus, normal driving contains the conditions for change blindness every few seconds. Thus, movement and luminance cues must be able to “break through” such change blindness effects in everyday driving.

A simpler explanation for “change blindness” effects on event detection during driver is given by studies on the underlying neural basis for spatio-temporal vision. The vision system is structured in such a way to sample the spatio-temporal derivatives in the visual field [23,24]. If a temporal change happens (such as brake lights on a forward vehicle suddenly turning on), it triggers many “transient” neurons in the visual system which respond to rapid luminance changes. These serve to alert the driver to direct covert attention to that location, usually followed by an eye movement to that location. If the sensory information were blocked because of a blink, saccade, or eye glance off the road, the neural transient arising from the visual stimulus would not occur. When the driver's eyes are back on the road ahead, the brake lights of the forward vehicle might still be on. The driver may then perceive the higher contrast of the illuminated brake lights against the background, or the looming of the forward vehicle as it decelerates. However, the response time of the driver will be slightly slowed because of the loss of the transient information, and the slighter later time of the visual information input.

Inattention blindness is also not likely in real-world driving. The phenomenon of inattention blindness can only be demonstrated in a single trial. When the subject becomes aware of the visual change or event, it is not missed again. In

the study of Young and Angell [12], the event stimuli were presented hundreds of times to each driver, through the course of all the tasks they completed. In the experiment of Angell et al. [11] the events were presented only once per trial. Yet the dimensions of driving performance, and the relationship of event detection variables to them, came out about the same in both studies (Young [4]). Hence, “eyes off the road” and “cognitive distraction” (as it relates to event detection) seem to be better explanations for reduced event detection performance during driving [4] than change or inattention blindness.

2.3. GAZE CONCENTRATION

The term *gaze concentration* refers to the narrowing of eye scan patterns. The eye gaze is directed relatively more frequently to the forward field of view, at the expense of the peripheral field of view. Gaze concentration is measured as an increase of the percentage of eyes-on-road time during for a secondary task. As cautioned by Angell [26, endnote 5] and Recarte and Nunes [27], gaze concentration is a separate and distinct mechanism from cognitive tunneling (Section 2.1). Is gaze concentration a useful metric for cognitive distraction?

Many studies find a concentration of gaze more towards the road center during auditory-verbal tasks as compared to visual-manual tasks: for example, cell phone conversations, or artificial auditory-vocal “cognitively demanding” tasks such as “n-back.” Likewise, Angell et al. [11, p. 8-28] found long times looking forward at the road particularly occur for auditory-vocal tasks. Cognitive load appeared to lead to a situation “... in which gaze was directed at the forward road, scanning of the mirrors was reduced somewhat (though to a lesser extent than for visual-manual tasks) and some peripheral events were missed (though to a lesser extent than for visual-manual tasks).” It is plausible that with longer looks to the roadway and less scanning of the mirrors, that detection of events reflected in those mirrors will get worse. However, note that this “gaze concentration” effect is not because of a reduction in the useful field of view, reduced sensitivity in the periphery, or “looked but did not see.” It is rather an example of “did not look so did not see.”

Many studies conjecture that gaze concentration is a driving safety hazard. This conjecture is inconsistent however to the well-established finding that relative crash risk is decreased to the extent that the eyes are on the road (Klauer et al. [28,45]). In fact, eyes off the road in the few seconds before a crash was shown by Klauer et al. studies [28,45] as being the single best predictor of relative crash risk in a wide range of driver performance variables examined. If the driver increases gaze concentration during a secondary task, then how could crash risk be increased?

The first argument made by those who say that gaze concentration increases crash risk is that increased gaze concentration is associated with “cognitive distraction,” causing “looked but did not see” errors (this argument is often associated with claims of change or inattention blindness as described in Section 2.2). That is, having eyes on

the road may not be sufficient to reduce crash risk - the “mind’s eye” must also be on the road (e.g., “mind on the drive,” as in the 1938 Buick commercial [2] quoted in the Introduction). If so, then when the “mind’s eye” is off the road, then the response to events in the forward roadway must be worse than during normal baseline driving, elevating relative crash risk. One way to test this conjecture is to examine event detection data when the eyes are on the road during auditory-vocal secondary tasks with known increases in gaze concentration. This conjecture would predict that more visual events are missed or response times are slowed during periods of gaze concentration. However, the CAMP-DWM investigators [11] found that auditory-vocal tasks with more gaze concentration had only slight decrements for detection of events on the forward roadway, and these were much smaller than the decrements observed for visual-manual tasks with less gaze concentration. No statistical significance testing for event detection was done in the original CAMP-DWM study [11], but Angell [26, her Fig. 4; 29] re-analysed the CAMP data statistically and showed that there was a statistically significant decrement in response for visual-manual tasks, but not for auditory-vocal tasks.

The second argument is that in some situations, glances off the roadway to critical safety-related locations reduce relative crash risk, so in these situations gaze concentration would increase crash risk. For example, glances to the rear or side view mirrors improve crash risk relative to baseline driving as shown by Klauer et al. [28,45]. That is plausible when you consider that before changing lanes for example, the driver who does not glance in the side mirror (and/or make a head turn over the shoulder) is at increased risk for a crash if a vehicle is in the adjacent lane. However, if a driver is intending to stay in the lane for example, why would not glancing to the side mirrors increase crash risk?

Instead, gaze concentration may indicate that the driver is attempting to drive more safely, not less safely. This hypothesis is known as “compensation.” Young and Schreiner [43] in a large study of 3 million drivers and 2,037 real-world airbag-deployment crashes looked at crash association with hands-free personal conversations made with the OnStar hands-free calling system. The found no increase in relative crash risk, even though it is well established that hands-free cellular conversations increase the response time to a visual event [30], and the brain mechanisms that give rise to an increased visual response time from conversation during driving have been specifically identified in brain imaging studies [31,32]. Young and Schreiner [43] proposed several behavioral mechanisms that could compensate for the increase in visual event response times during cell phone conversations. Observational studies with portable cell phones show that drivers adapt phone conversations to the driving environment, and also adapt their driving behavior to the content of the phone conversations [33,34]. Mazzae et al. [35] found that drivers made fewer calls in heavy traffic than in light traffic, especially when using hands-free phones. Drivers might also tend to engage in calls in less-demanding