Assessing the effect of in-vehicle task interactions on attention management in safety-critical events

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Abstract: Two analytic techniques were applied to study patterns of on- and off-road glances in naturalistic driving. The dataset used in this study was the Naturalistic Engagement in Secondary Task (NEST) database, a subset of the Strategic Highway Research Program (SHRP2) database, which contains safety-critical event (SCE) data comprised of Crash and Near-crash epochs curated so as to only contain incidents linked to secondary task activity. Output from an attention buffer, which produces a hybrid metric based on how on- and off-road glances are threaded over time, was analyzed in a comparison of safety-critical events to Baseline driving. Individual glance metrics of mean single glance duration (MSGD), number of glances, and proportion of glances by location, binned in 5-s intervals, were also analysed to diagnose the underlying behavioural patterns produced from the attention buffer. Statistical comparisons between SCEs and Baseline driving showed that regardless of secondary task type, during SCEs, drivers exhibited a destabilization of attention over time not evident in Baseline driving. Further examination of these effects based on an analysis of accumulated buffer loss revealed a more pronounced fracturing of attention over time for epochs containing visual-manual secondary task activity than those containing only auditory-vocal secondary task activity.

1. Introduction

A recent analysis of safety-critical events from the 100-Car Naturalistic Driving Study revealed the importance of on-road glance length in-between off-road glances in the moments preceding near-crash and crash outcomes [1]. In the 25s of time prior to these events, drivers involved in near-crashes (i.e., averted crashing) had significantly longer on-road glances, and looked less frequently between on- and off-road locations as compared to those involved in crashes. The authors showed that patterns of glance between on- and off-road locations differentiated safety-critical events (SCE) due to cumulative effects produced from the length of time drivers glanced to each location. These time-history effects were evident in consecutive time-bins of mean single glance duration (MSGD) and in output produced from the AttenD algorithm [2]. Based on these findings, the authors called for the use of metrics and analytic techniques that allow for a comparison of different glance sequences to multiple locations to complement existent assessment methods focused on single-region (commonly, off-road) glance allocation [3].

To further examine the extent to which the duration of on-road glances threaded between off-road glances produce patterns linked to safety-critical outcomes, the same analytic techniques introduced in [1] were applied to an analysis of a subset of SCEs from the Strategic Highway Research Program (SHRP2) naturalistic driving study [4] contained within The Naturalistic Engagement in Secondary Task database (NEST). The consideration of data from NEST allows for a more in-depth analysis on the extent to which the glance behaviours evident in the safety-critical epochs from the 100-car dataset are descriptive of a common pattern of attentional mismanagement in the moments prior to crashes and near-crashes, and/or, are preconditioned on interactions contingent on secondary task type. Unlike the 100-Car dataset, SCE epochs within NEST are all known to include secondary tasks. This additional coding of secondary activity enables an exploration of how task type disrupts glance behaviour in the moments prior to a precipitating event compared to Baseline driving. It is hypothesized that drivers engaged in secondary tasks display a destabilized glance pattern as compared to Baseline driving. Further, tasks that impose higher visual load are anticipated to produce increased destabilized patterns compared to those which primarily draw upon cognitive resources [5].

2. Method

The dataset used in this study was the Naturalistic Engagement in Secondary Task (NEST) database [4], a subset of the Strategic Highway Research Program (SHRP2) database, containing safety-critical event (SCE) data comprised of Crash and Near-crash epochs curated so as to only contain incidents linked to secondary task activity, as well as four Baseline epochs (i.e., epochs that do not contain SCEs) from each driver for each of that driver's independent observations in the SCE set. All the SCE epochs contain secondary task activity, which we categorized as visual-manual (e.g., any reaching, adjusting, manipulating, or holding activity), auditory-vocal (e.g., any conversation activity with a passenger, on the phone, or via voice commands to an in-cab system), or "mixed-mode," containing both kinds of secondary task activity (see Table 3 in Appendix A for a list of secondary tasks in NEST and how they were categorized, as well as how many epochs were observed for each type of SCE). Baseline epochs contained a mixture of those containing secondary task activity and those without, in order to reflect a truly random sampling of behaviour for those drivers found in the NEST SCE set. In the following analyses, "Baseline" values are always drawn from this mix of epochs, some of which contain secondary tasks, some of which do not. For example, when Crash epochs containing auditory-vocal tasks are compared to Baseline epochs, the comparisons are made within-subject, but behaviours observed are limited to those Crashes containing auditory-vocal tasks, while all Baselines are aggregated regardless of secondary task activity present, so as to compare behaviours during SCEs that are potentially linked to categories of secondary task behaviour to drivers' own typical behaviours (i.e., randomly selected) in routine driving.

Crash and Near-crash epochs were selected from exclusive groups of drivers, because, in NEST, Crash epochs outnumber Near-crash epochs. In cases where a single driver had both Crash and Near-crash epochs, the Crash epochs were removed, so that all statistics were computed on independent samples. This filtering yielded a set of 78 Near-crash epochs, 133 Crash epochs, and 940 Baseline epochs. For visualizations and statistical comparisons, epochs were further aggregated within drivers (because a single driver occasionally appeared in multiple SCEs of the same type, and always appeared in multiple Baseline epochs), yielding a set of 67 Near-crash drivers, 127 Crash drivers, and equivalent Baseline epochs.

For analyses utilizing the attention buffer, this set was further reduced by eliminating epochs that did not contain at least 19 seconds of glance data. The set was still further reduced by removing epochs from the SCE sets that did not have corresponding epochs in each driver's matched Baseline set; each secondary task grouping (Auditory-vocal, Visual-manual, and Mixed-mode) contained epochs from both SCE and Baseline sets for each driver in order to compute within-subject comparisons between Baseline and SCE. The dataset was further trimmed so that Crash and Near-crash epochs contained fully non-overlapping sets of drivers. This further filtering yielded a set of drivers, organized by task composition of epochs, shown in Table 1.

Table 1 Number of drivers, by SCE type and task composition for attention buffer analyses

	Near-crash	Crash
Auditory-vocal	5	17
Mixed-mode	12	29
Visual-manual	35	36

The primary behaviour of interest was glancing: In NEST, glance behaviour is provided in a sample-by-sample format, at 10 Hz, with each sample coded with an area-of-interest. For SCE epochs, only glance data prior to the onset of the precipitating event of the SCE was used, up to 20 seconds; for Baseline epochs, entire epochs were used, up to 20 seconds. Epochs that did not contain at least 19 seconds of data were excluded; thus, the entire data set consisted of 20 second epochs that either entirely preceded an SCE or was routine (Baseline) driving drawn from the sample of SCE drivers. From these periods of glance behaviour, four glance statistics were computed: mean single glance duration (MSGD), number of glances, proportion of glances to a location, and mean attention buffer value. Off-road locations in the vehicle that were designated as irrelevant for driving-related situation awareness included the driver's cell phone, iPod, or other interior objects, the centre stack, passengers, over-the-shoulder, or periods of time where the eyes were closed or were otherwise clearly off-road, even if not visible. Off-road locations in the vehicle that were designated as relevant to driving-related situation awareness included the instrument cluster, rear-view mirror, and left and right windows or side mirrors. On-road peripheral locations included the left and right windshield, while the main on-road location was coded as forward. For all three of the typical glance measures (MSGD, # of glances, and proportion of glances to a location), values were averaged first within drivers across available epochs, and then across drivers.

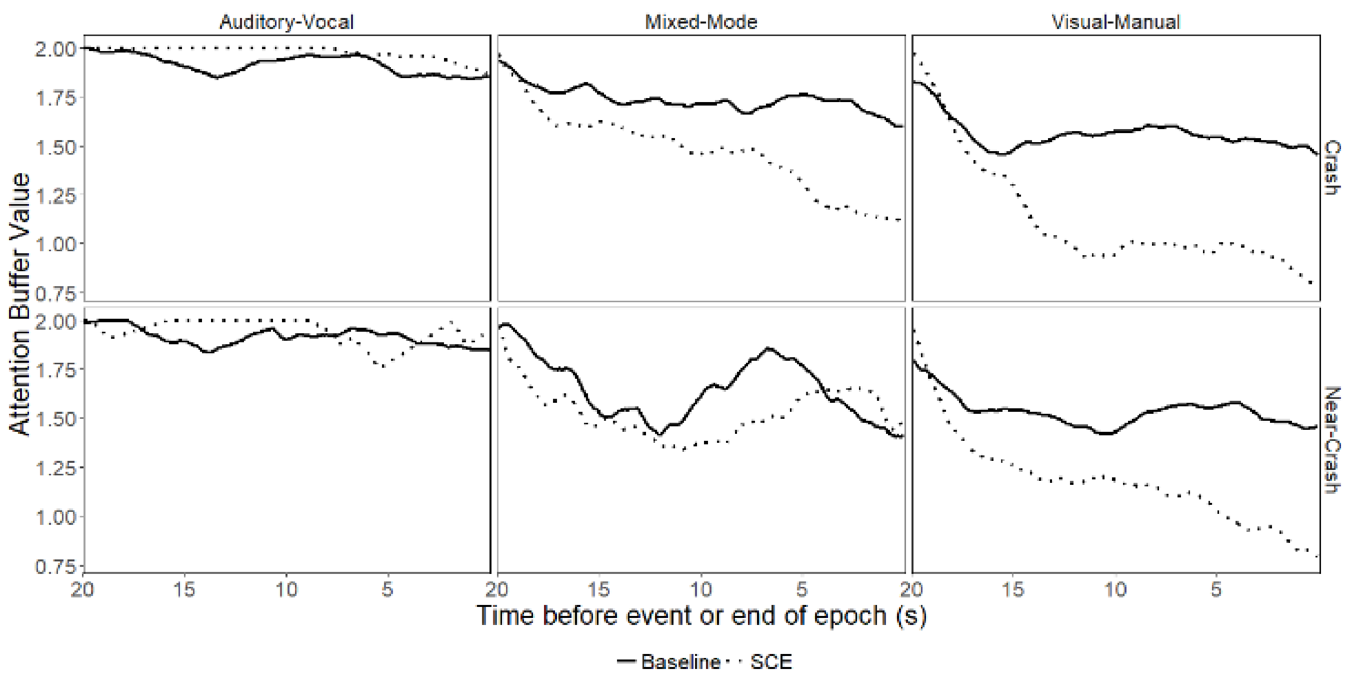

__Fig. 1.__ Attention buffer by type of SCE and secondary tasks

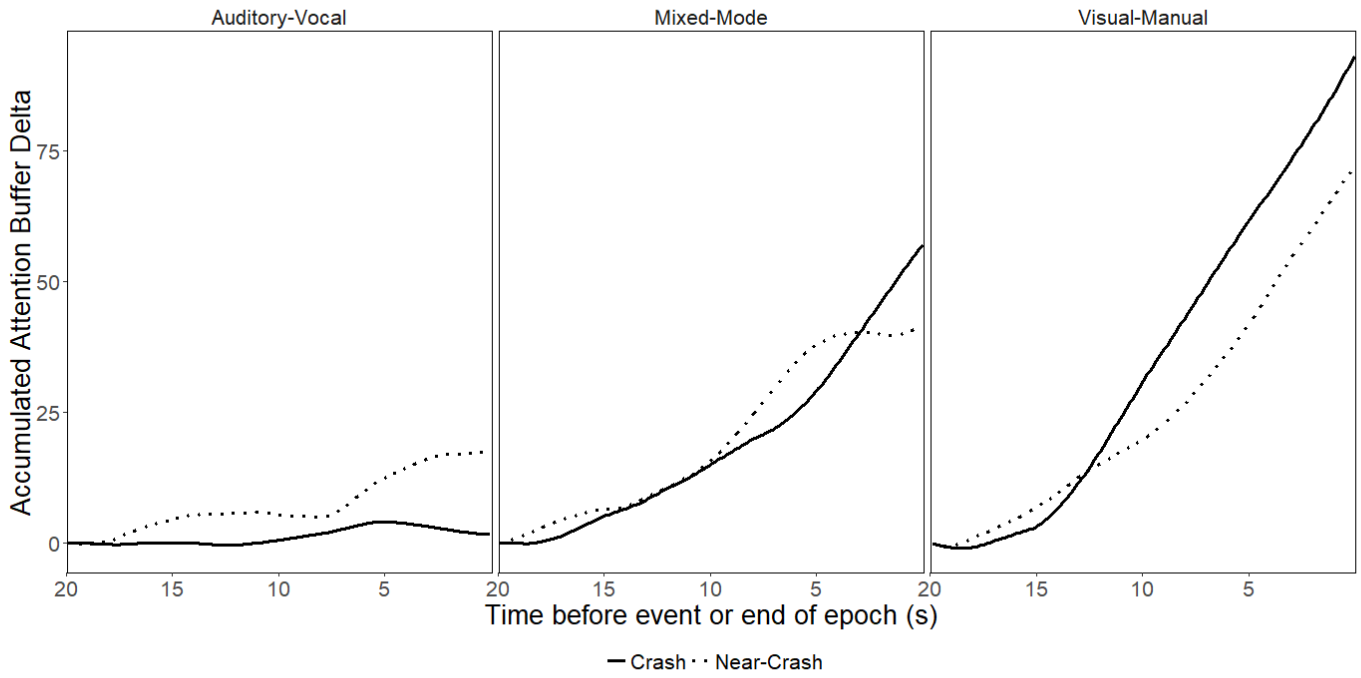

Fig. 2. *Accumulated difference in attention buffer between SCE and Baseline by SCE type and secondary task composition*

Averages were plotted with standard error of the mean bars to reflect the variance across drivers.

For the attention buffer measure, a modified form of the AttenD algorithm, first described within [6], was applied on an epoch-by-epoch basis. In its modified form, the Attention Buffer represents the amount of stored information about the roadway. Its value is tied to processes of attention and memory that are at play in how drivers sample information to form, retain, and update a robust representation of the driving environment [1]. At the start of each epoch, the initial buffer value was set at 2. For each second of off-road glance, the buffer value was decremented by 1 point. If the AttenD value reached 0, it did not drop further until the driver glanced back to the forward road, at which point it began increasing again, after a latency period of 0.2 seconds, reflecting an experimentally-derived minimum time required, following from an attentional shift, to perceive the presence and relative location of elements that have meaning for maintaining safe travel and anticipating potential hazards [7]. The rate of increment once glance returned to the forward road was set at a rate of 0.33 points per second, until it returned to 2 points. This rate specifies an average value corresponding to the amount of on-road glance time it takes to fully perceive and comprehend the presence of a slow-moving, non-salient, or peripherally-located hazard [8-12]. Glances to mirrors and the instrument cluster did not result in a decrement of the buffer until the duration exceeded 1 second, at which time the buffer decremented by 1 point per second. An up to 1-second time delay for these regions was included because they contribute to situationally-aware driving. Visualizations of the buffer data were made by averaging across epochs per type (i.e., near-crash, crash, baseline) for each time point within the 19-20 seconds (190-200 samples).

3. Results

Results are first presented for attention buffer analyses; later, differences between attention buffer profiles are explored in terms of traditional glance metrics.

Attention buffer scores were aggregated first by subject within each group of secondary tasks (Auditory-vocal, Visual-manual, and Mixed-mode), and then across drivers for each sample point in the 19-20 second period before a precipitating event (in SCE epochs) or the end of the epoch (in Baselines). Thus, each sample point becomes an average of averages, with more epochs aggregated in Baseline. Each SCE aggregated buffer line is plotted next to the aggregated Baseline buffer line from its matched drivers who had the same epoch secondary task composition within their Baseline periods. These plots can be seen in Fig. 1. Across the secondary task groupings, the slope of each buffer line, from the earliest moments before the end of an epoch, to the end of the epoch, tends to be negative, but changes in steepness as the task composition moves from Auditory-vocal, to Mixed-mode, to Visual-manual. For Auditory-vocal epochs, these lines, whether Near-crash or Crash, and whether Baseline or SCE, appear flat, suggesting there is no recorded loss of (visually-based) driving-related situation awareness across the span of the epoch. However, starting with Mixed-mode epochs, differences appear visible for Crash epochs between their SCE and Baseline counterparts, while less of a distinction appears for Near-crash epochs. For Near-crash Visual-manual epochs, the difference does appear, and the difference between SCE and Baseline attention buffer appears to be the greatest in magnitude between the Crash Visual-manual SCE and Baseline epochs.

Table 2 LME coefficients for attention buffer slope analyses

Sec. Task	Model Term	*B*	Std. Error	*t*
Visual-manual	Time	0.00320	0.00007	42.69***
	SCE Type	-0.07284	0.17570	-0.42
	Time x SCE Type	-0.00057	0.00015	-3.79***
Auditory-vocal	Time	-0.00001	0.00005	-0.12
	SCE Type	0.03491	0.05013	0.70
	Time x SCE Type	0.00023	0.00011	2.08*
Mixed-mode	Time	0.00161	0.00012	13.71***
	SCE Type	-0.15200	0.22660	-0.67
	Time x SCE Type	-0.00343	0.00026	-13.43***

* = $p < .05$; *** $p < .001$

To assess the statistical significance of these apparent differences in slope, linear mixed effects (LME) models [13] were computed, regressing the difference between drivers' aggregate Baseline buffer score and their SCE buffer score against the time point of each sample. These were computed separately, by task composition, and the interaction between time in epoch and type of SCE (Crash or Near-crash) was also assessed as a second-order effect. These results can be seen in Table 2 For each type of secondary task composition, the change in the attention buffer from matched Baseline driving, engaged in the same category of secondary tasks, displayed a significantly different slope over time as a function of whether that time period immediately preceded a Crash or a Near-crash. For Mixed-mode and Visual-manual epochs, this difference was due to a steeper slope in Crashes than Baseline, compared to Near-crashes and Baseline; for Auditory-vocal epochs, the effect was reversed, and far more subtle.

In addition to comparing the average difference, time point by time point, between SCE and baseline epochs, we also looked at the accumulation of this difference over time, in what can be interpreted as an area-under-the-curve, depicting the accumulated effect of aggregated loss of situation awareness versus Baseline driving within a secondary task modality. These effects are visualized in Fig. 2. Overall, the accumulated loss of (visually-mediated) driving-related situation awareness is greater in the Crash epochs containing Visual-manual tasks; this accumulated loss shows a steeper decline (shown here by a more positive slope) than Near-crash epochs of the same modality. LME analyses suggest that Auditory-vocal and Visual-manual accumulated attention buffer changes differ significantly over time between Crash and Near-crash epochs ($p < .001$ for both models).

These two sets of effects suggest that driver glance behaviour is different between Crash, Near-crash, and Baseline epochs, even when those epochs are controlled for both driver and the modality of secondary task composition. To better understand what specific glance behaviours may be driving these effects, we examined patterns in glances to different areas of interest across these groups using three measures: mean single glance duration, number of glances, and glance proportion.

For mean single glance duration, mean statistics were computed for on-road glances and off-road glances, as well as for Crash, Near-crash, and Baseline epochs; furthermore, statistics were computed separately for SCE epochs that contained Auditory-Vocal tasks, Visual-Manual tasks, or a mix of the two. Furthermore, glances were "binned" based on the time point at which the glance was initiated; for example, a glance initiated 18 seconds before the end of the epoch was placed in the 15-20 s bin. While long glances may straddle multiple 5 s bins, glances are only placed in the bin in which they are initialized; because glances can be long (especially on-road glances), mean glance duration tends to drop as bins get closer to the end of an epoch, due to the temporal limit on how long they can be sustained given the available window. Average glance duration for forward glances is presented in Fig. 3, and MSGD for other locations is presented in Fig. 4. Note that for each "Baseline" mean single glance duration value, it is the same across all types of task composition (because it represents typical, non-SCE driving performance randomly sampled from SCE drivers, and is being contrasted with SCE glance behaviour linked to different categories of secondary tasks).

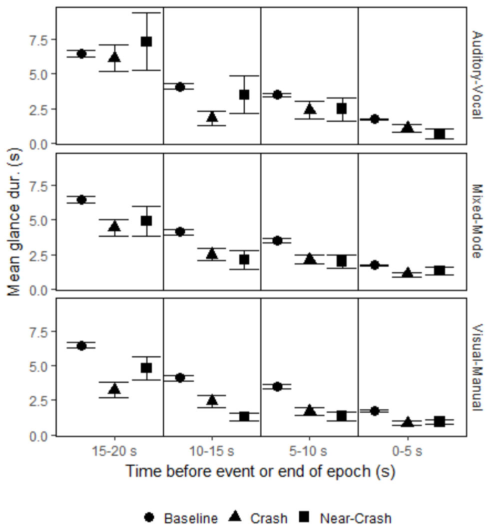

Fig. 3. *MSGD for forward glances by time to event, task modality, and SCE type. Error bars indicate standard error*

Average glance counts for each location are presented in Fig. 5, and average glance proportion—the proportion of each bin subtended by glances to a specific location—are presented in Fig. 6.

In comparing glance behaviour across Crash, Near-crash, and Baseline epochs, comparisons were done as repeated measures t-tests. Notably, *p* values were not

Bonferroni-corrected, as the available data within a cell was sparse and the number of comparisons was large; thus, the probability of a type I error is likely high. However, our goal was to examine the trends of glance differences within temporal bins, and to identify the bins with the greatest likelihood of being associated with significant differences in glance behaviour between SCE epochs and Baseline epochs. Thus, it is important to recognize that,

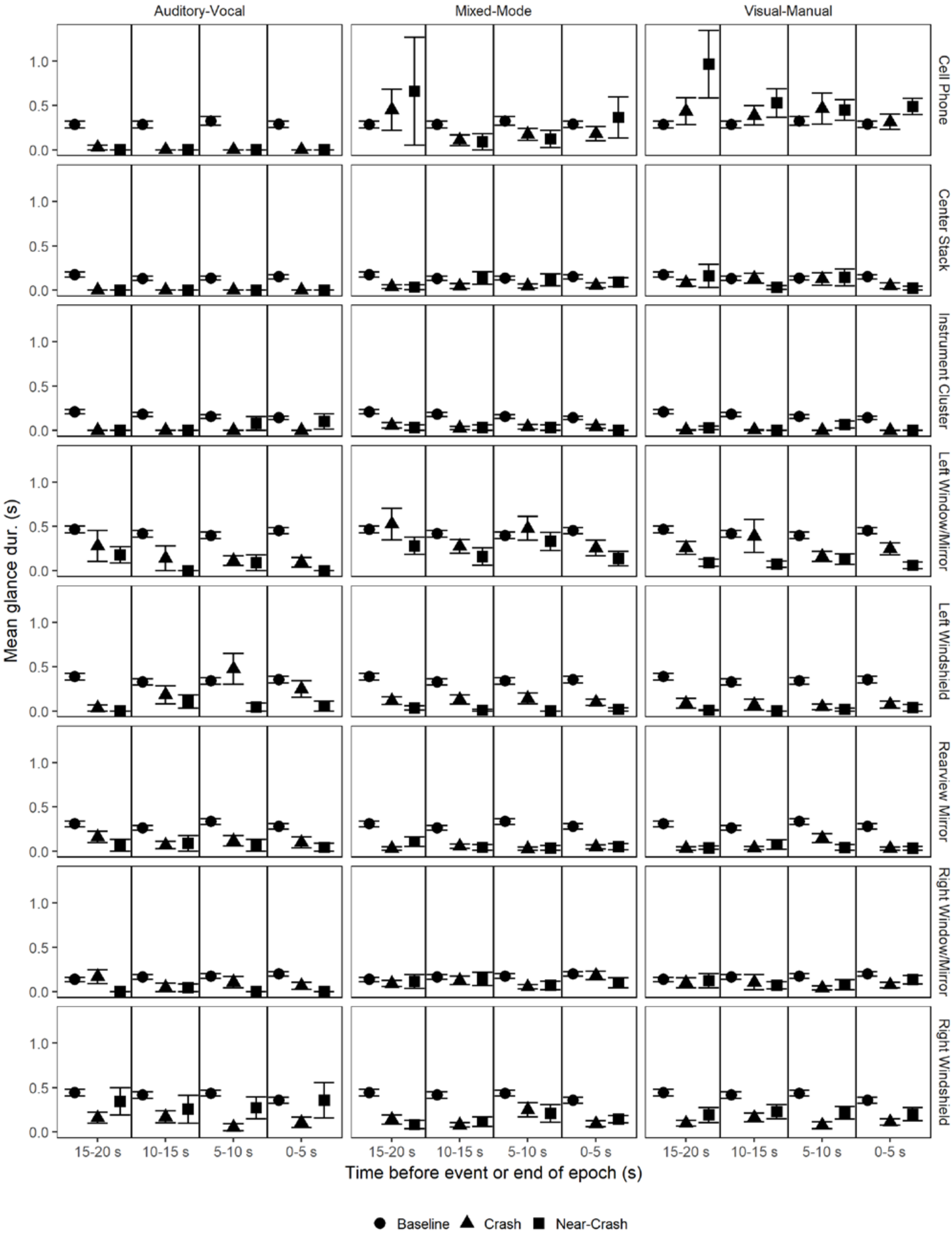

Fig. 4. *MSGD (s) by location, task modality, and SCE type. Error bars indicate standard error*

were the tests to be repeated on a new set of data, finding significant differences within any given bin with a similarly sized sample may not be successful; however, this binning approach provides a guide as to when differences emerge in the moments preceding precipitating events.

The greatest differences between SCE and Baseline glance duration occurred in the bins farthest away from the end of the epochs (i.e., farthest away from the precipitating event in SCE epochs): the 15-20 s bin, $t(33) = 2.35$, $p = .025$, and the 10-15 s bin, $t(36 = 2.75$, $p = .0093$. Smaller, but significant differences were observed in the 5-10 s bin, $t(34) = 2.15$, $p = .039$, and 0-5 s bin, $t(36) = 2.2$, $p = .034$. Near-crashes were associated with longer off-road glances in the 15-20 s bin $t(22) = 2.21$, $p = .038$, the 10-15 s bin $t(21) = 2.15$, $p = .044$, and the 5-10 s bin, $t(28) = 3.41$, $p = .002$). For Mixed-mode epochs, only the Crash 15-20 s bin, $t(35) = 1.78$, $p = .083$, and Crash 0-5 s bin, $t(39) =$

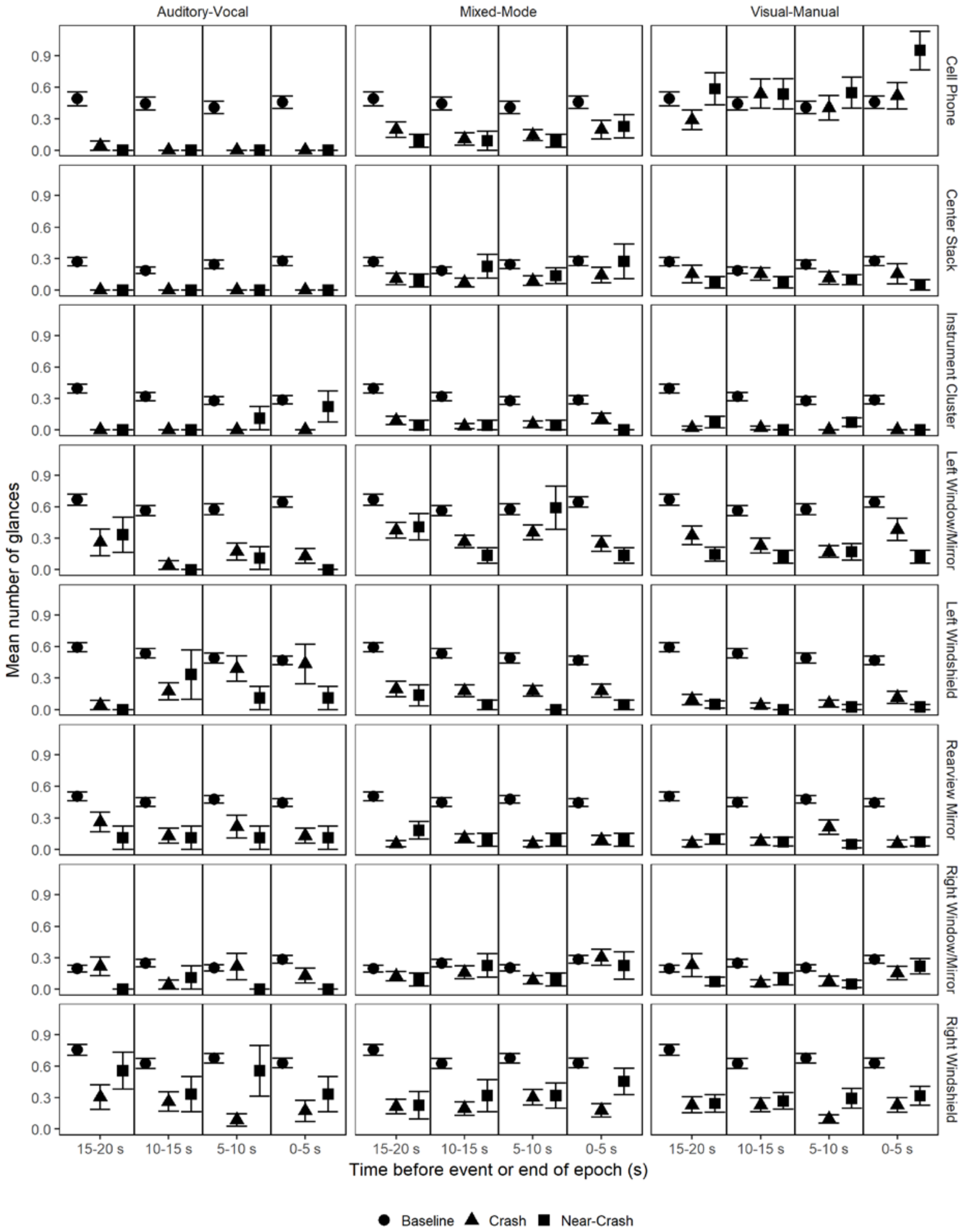

Fig. 5. *Mean number of glances by time to event, location, task modality and SCE type. Error bars indicate standard error*

1.73, p = .092, had marginally significant longer off-road glances than Baseline. No Near-crash off-road glances in any bin were significantly different than Baseline glances for Mixed-mode epochs. The only off-road difference observed in Auditory-vocal epochs were for Near-crashes, in the 5-10 s bin, $t(3)$ = 3.78, p =.03, with longer off-road glances being observed in baseline driving.

Mean on-road glances were shorter in Crash visual-manual than Baseline epochs in the 15-20 s bin, $t(48)$ = 2.12, p = .039, 5-10 s bin, $t(39)$ = 2.04, p = .049, and 0-5 s bin, $t(40)$ = 2.74, p = .0093; for Near-crash, significant differences were observed in the 5-10 s bin, $t(30)$ = 2.54, p = .017) and 0-5 s bin, $t(34)$ = 3.25, p =.0026, and a marginal difference was observed in the 10-15 s bin, $t(24)$ = 2.06, p = .051; notably there was no effect in the farthest bin, suggesting that one critical difference between Near-crash and Crash epochs containing visual-manual activity is that the differences in glance behaviour, compared with Baseline, extend only to time periods closer to the SCE. No significant differences were observed between Near-

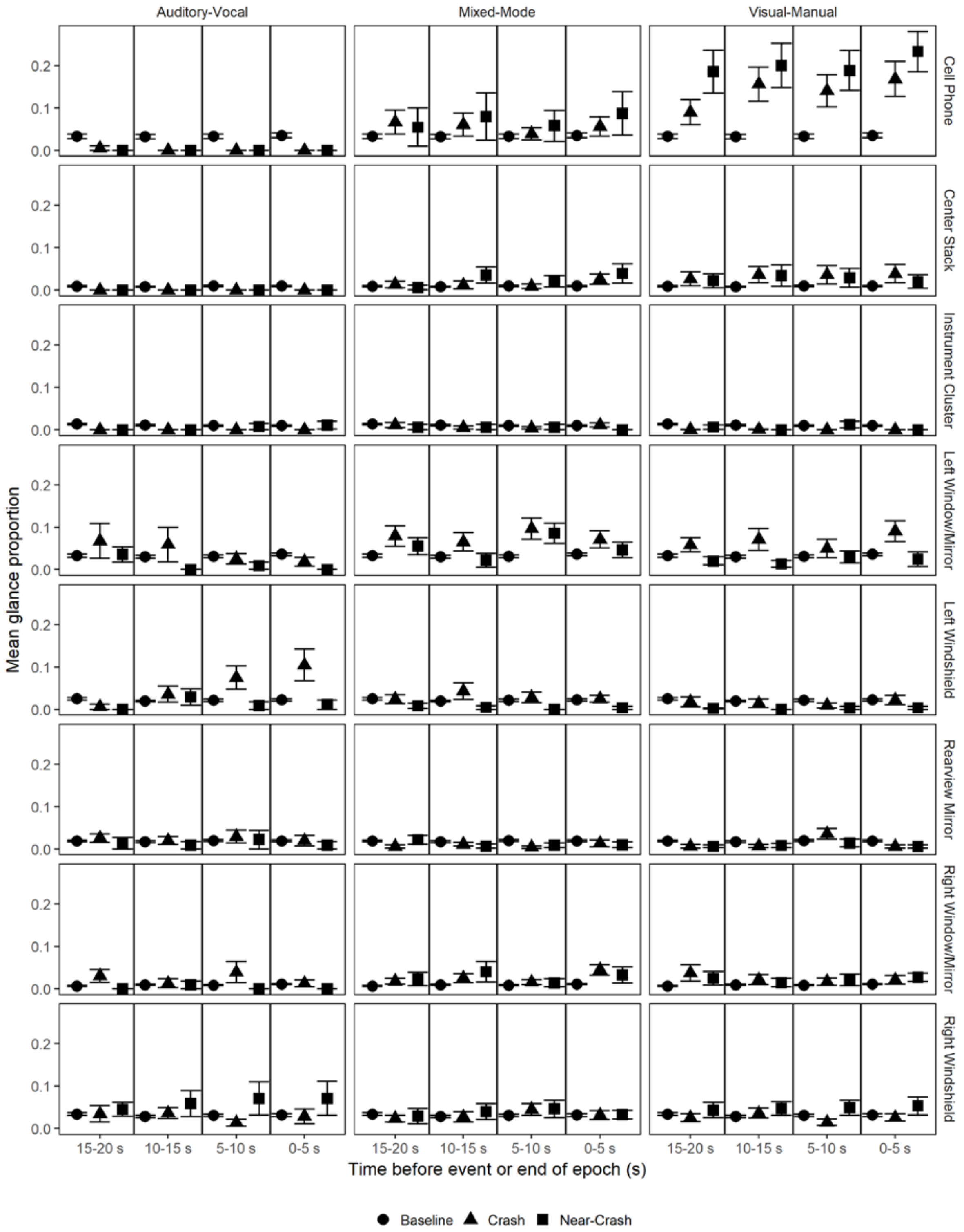

Fig. 6. *Mean glance proportion by location, task modality, SCE type and time to event. Error bars indicate standard error*

crash and Baseline and Crash and Baseline epochs containing Auditory-Vocal or Mixed-mode compositions of tasks; statistics suggest that, for SCEs containing Auditory-Vocal tasks, the trend is in the opposite direction, in the bins farthest from the precipitating events, with on-road glancing being longer in the SCE conditions than typical Baseline driving.

4. Discussion

The attention buffer provides a hybrid metric that reflects temporal patterns in how drivers allocate glances on- and off-road. The buffer concept represents information a driver can encode from the driving situation during on-road glances as well as the resulting loss of information when the driver looks away from the road. This metric produces a signal representative of how attention is managed over time and space. Statistical comparisons between SCEs and Baseline driving showed that regardless of the modality of secondary task composition, during SCEs, drivers exhibited a destabilization of attention over time not evident in Baseline driving. Further examination of these effects based on an analysis of accumulated buffer loss revealed a more pronounced fracturing of attention over time for epochs containing Visual-manual secondary task activity than those constrained to Auditory-vocal activity, evident from steeper negative slopes. These results suggest an accumulated risk in how glances are threaded over time and space when drivers deviate from how they attend to secondary tasks in Baseline driving.

Unlike patterns produced when drivers are engaged in visually-loading secondary tasks, those evident from buffer analyses of periods of performance of auditory-vocal secondary tasks indicate gaze centralization to the forward roadway. While allocation of glance to central and peripheral road regions was not accounted for in the current attention buffer implementation, the patterns produced from SCEs with auditory-vocal secondary task activity derive from long on-road glances, which have been linked to cognitive load [14, 15].

Exploration of the standard glance metrics of mean single glance duration (MSGD), number of glances, and proportion of glances to a location help to diagnose the underlying behavioural patterns produced from the buffer metric. Akin to the findings in the 100-car analysis [1], the analysis of MSGD for on- and off-road locations during SCEs indicated that, as compared to periods of baseline driving, when drivers fail to protect their ability to anticipate hazards via upstream reductions in the length of time glancing to forward roadway, they suffer a loss of awareness of the environment that disrupts how attention is managed in subsequent moments. This disruption leads to ill-timed glances off-road, reduced frequency of glances to SA-relevant locations, or to glances to inappropriate locations in the moments prior to precipitating events.

Breakdowns by task modality for these measures point to fewer, shorter glances to the forward roadway and to SA-relevant off-road locations, as well as to more frequent, longer glances to SA-irrelevant locations ascribed to the period 15-20s in advance of precipitating events for epochs that contain visually-loading secondary task activity. For those epochs that contain only auditory-vocal secondary task activity, drivers exhibited reduced sampling to both situationally-relevant left windshield and right window/mirror in the moments preceding a precipitating event, as early as 15-20s in advance of these events.

Following on from the analysis of the 100-car dataset [1], this analysis of a second naturalistic dataset provides further evidence of common patterns of attentional mismanagement in the moments prior to crashes and near-crashes that are distinctly different from periods of baseline driving. Viewed from the perspective of attention management, metrics like the attention buffer are able to produce time-history signatures of glance behaviour that reveal cumulative effects with safety-relevant implications.

5. Acknowledgment

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6. References

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7. Appendix A

Table 3 NEST tasks by SCE type

Task	Baseline			Crash			Near-crash		
	AV	MM[1]	VM	AV	MM	VM	AV	MM	VM
Adjusting/monitoring climate control	0	4	16	0	3	0	0	1	0
Adjusting/monitoring other devices integral to vehicle	0	5	10	0	4	1	0	1	3
Adjusting/monitoring radio	0	24	51	0	5	9	0	3	4
Applying make-up	0	1	1	0	0	0	0	0	2
Biting nails/cuticles	0	5	20	0	1	1	0	1	3
Brushing/flossing teeth	0	0	1	0	0	1	0	0	0
Cell phone	0	27	63	0	7	10	0	5	14
Child in adjacent seat - interaction	1	4	0	0	0	0	0	1	0
Child in rear seat - interaction	3	4	0	0	1	0	0	0	0
Combing/brushing/fixing hair	0	4	4	0	3	0	0	0	0
Dancing	0	25	8	0	1	1	0	2	1
Dialling hand-held cell phone	0	2	0	0	3	0	0	0	0
Dialling hand-held cell phone using quick keys	0	0	0	0	1	0	0	0	0
Drinking	0	7	14	0	2	1	0	0	1
Eating	0	3	15	0	2	3	0	0	2
Inserting/retrieving CD	0	1	0	0	0	1	0	1	0
Locating/reaching PDA/ other handheld device	0	1	0	0	0	0	0	0	0
Locating/reaching/answering cell phone	0	15	27	0	3	7	0	4	8
Looking at an object exter0l to the vehicle	0	32	54	0	18	11	0	11	8
Looking at pedestrian	0	1	4	0	1	1	0	0	0
Looking at previous crash or incident	0	1	0	0	0	0	0	0	0
Moving object in vehicle	0	0	2	0	2	0	0	1	0

[1] The mixed mode (MM) category was used whenever an epoch contained both visual-manual (VM) activity and an auditory-vocal (AV) activity. For example, if an epoch contained a VM activity (e.g., "looking at an object external to vehicle") and, within the same 20s period, an AV activity took place (e.g., "conversation"), then it was classified as a MM epoch.

Object dropped by driver	0	0	0	0	0	1	0	0	1
Object in vehicle	0	16	25	0	12	7	0	1	6
Operating PDA/ other handheld device	0	1	2	0	0	0	0	0	0
Other external distraction	0	28	49	0	12	10	0	2	5
Other personal hygiene	0	9	17	0	2	4	0	1	3
Passenger in adjacent seat - interaction	107	63	0	9	23	0	5	9	0
Passenger in rear seat - interaction	12	10	0	3	4	0	0	1	0
Reaching for food- related or drink-related item	0	3	7	0	1	4	0	0	0
Reaching for object that is a manufacturer-installed device	0	1	1	0	1	0	0	0	0
Reaching for object	0	6	14	0	10	5	0	2	4
Reaching for personal body-related item	0	0	2	0	0	1	0	0	1
Reaching for, Lighting, Smoking, Extinguishing cigar, cigarette	0	8	10	0	1	2	0	1	2
Reading	0	0	0	0	1	0	0	0	0
Removing/adjusting jewellery	0	3	1	0	0	1	0	0	1
Removing/inserting/ adjusting contact lenses or glasses	0	4	3	0	1	2	0	0	0
Talking/listening on cell phone	33	13	0	11	7	0	5	2	0
Talking/singing	83	91	0	2	26	0	0	11	0
Texting on cell phone	0	15	70	0	6	15	0	4	18
Viewing PDA/ other handheld device	0	1	2	0	0	0	0	0	0
Writing	0	0	0	0	0	1	0	0	0