

## FOCAL AND AMBIENT VISUAL CONTRIBUTIONS AND DRIVER VISUAL SCANNING IN LANE KEEPING AND HAZARD DETECTION

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In some previous simulator studies, we showed that drivers, engaged in a secondary in-vehicle task at different display separations, were able to buffer some aspects of the driving task (e.g., vehicle control), but not others (e.g., hazard response; Horrey & Wickens, 2002, Horrey, Alexander, & Wickens, 2003). We speculate that this pattern of results may be a result of effective time-sharing between the *ambient* visual task of vehicle control and the *focal* visual in-vehicle task, but task interference between the in-vehicle task and the *focal* task of hazard detection and identification. Alternatively, drivers may be using an optimal scanning strategy that allows them to effectively monitor both the roadway and the in-vehicle device. In this paper, we detail some of the theoretical background, describe some relevant research, and present a model of scanning behavior.

Recently, there has been a growth of new in-vehicle technologies (IVTs) offering drivers a wide range of wireless web and cellular applications. As more IVTs are inserted into the automobile, drivers may be more inclined to use these devices while driving—an obvious safety concern, to the extent that these devices interfere with driver safety or compete with the already taxing visual demands of driving for limited visual resources (Wickens, 2002).

One important aspect in determining the nature of a driver's interaction with these devices is the location (or separation) of the in-vehicle display, relative to the outside world. In general, the information access costs associated with a particular display-set increase with display separation (such that longer scans are more detrimental to performance than are shorter ones). The implication is that a more proximal IVT display location (e.g., one presented in a head-up display) may yield superior performance for both the driving and IVT tasks.

In some previous experiments on IVTs, we examined performance on vehicle control (lane keeping) and hazard detection as drivers performed a concurrent IVT task (Horrey & Wickens, 2002; Horrey, Alexander, & Wickens, 2003). As drivers traveled through traffic environments of varying complexity, they received telephone information on different IVT displays and were asked to repeat the number, as if to enter it in a voice-activated phone system. As shown in Figure 1, the numbers were presented visually either (a) on a simulated head-up display (HUD), located just above the hood of the vehicle on the road ahead ( $7^\circ$  below the horizon); or (b) on a head-down display (HDD; approximately  $38^\circ$  offset from the driver's forward line of sight). In general, the results suggested that drivers were able to buffer some aspects of the driving task from degradation with the more separated display (e.g., vehicle control), but not able to protect other aspects (e.g., hazard response).

One plausible explanation for the dissociation of these two effects is that the tasks of controlling the vehicle versus those of detecting road hazards and reading the displayed digits use separate visual channels (Previc, 1998) and, therefore, certain combinations of tasks can be time-shared more effectively than others (Wickens, 2002). For example, lane keeping and speed control may utilize ambient vision, well-supported in the peripheral visual field, however, this may not be sufficient in the effective detection and identification of hazards, in

which case focal visual resources are required. Similarly, in-vehicle tasks requiring the discrimination of displayed digits, letters, and symbols utilize focal visual resources. As such, the successful concurrent performance of vehicle control (ambient) and the IVT task (focal) would be possible, even at the greater display separations, since they tap different visual resources. An analogous situation might be a mailperson, who can successfully walk down a sidewalk while reading the addresses on the next to-be-delivered mail. In this case, focal vision is directed towards the address labels, while ambient vision properly monitors the peripheral flow field. In contrast, the hazard detection and IVT tasks would be in direct competition for focal visual resources, resulting in task interference (and, as a consequence, degraded performance).

Alternatively, drivers may be simply employing an optimal scanning strategy that, for the most part, accesses the traffic environment and IVT display at appropriate times, allowing drivers to buffer certain aspects of vehicle control (e.g., Wierwille, 1993). That is, based upon the bandwidth of the road environment and the inertia of the vehicle, they are able to optimally schedule intermittent scans to the roadway to assure that the dynamic vehicle state is perfectly inferred (Moray, 1986; Senders, 1983). In short, the optimal scanning strategy predicts that eye movements will be directly driven by the input bandwidth (e.g., frequency of road curvature or wind gusts), whereas the multiple resource strategy, in its strongest version, predicts that successful lane-keeping can be accomplished with no upward scans at all, and in its weaker version predicts that the amount of upward scanning will need to be proportionately increased by higher input bandwidths.

In this paper, we will provide an expanded description of focal and ambient vision, review the findings from some relevant research, and discuss these concepts in the arena of driving performance and measurement of eye behavior.

### Focal and Ambient Visual Channels

Resource theories have been expanded in recent years to encompass multiple resources along the visual channel (e.g., Wickens, 2002). This addition differentiates between focal and ambient visual resources (Leibowitz & Post, 1982; Previc, 1998, 2000), which vary along a number of dimensions.

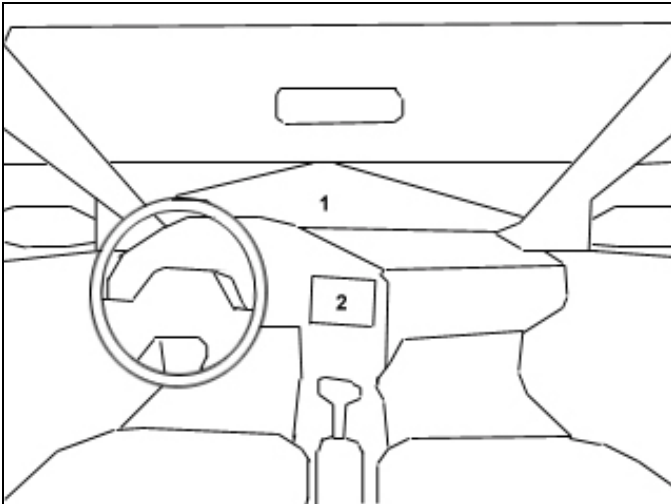


Figure 1. Display configuration for the (1) HUD and (2) HDD conditions used by Horrey & Wickens (2002) and Horrey et al., (2003). Adapted from Summala, et al. (1998).

Previc (1998) describes the primary function of the *focal* (or *focal extrapersonal*) visual system as visual search, object recognition, and related tasks requiring high visual acuity—this would include reading text). This system is predominantly ventrolateral (i.e., involving parvo visual cortical pathways spanning the occipital-temporal cortex). According to Previc (1998), this system is situated in the central 20 to 30° of the visual field, is upper field dominant (this bias may be because many focal-operations are carried out at a greater distance than close, e.g., searching an environment), spans from 0.2 meters to great distance in depth, relies on saccades as the primary motor system, and is centered in the retinotopic coordinate system.

In contrast, the *ambient* (or *ambient extrapersonal*; Previc, 1998) visual system is involved in orienting in earth-fixed space, spatial orientation and postural control in locomotion. Ambient vision is a predominantly dorsomedial neural activity. This system typically encompasses the front 180° of the visual field, is lower field dominant (because of the importance of optic flow information in ground-based locomotion), usually uses information at great depths, relies on a gravitational, earth-fixed coordinate system, relies on leg and head movements as the primary motor systems, and involves peripheral vision. This system relies on a few major visual cues, including horizontality cues, linear perspective, and motion flow however; it is not fastidious about scene details inasmuch as orientation and stability can be maintained even when vision is degraded considerably.

Leibowitz and colleagues (Leibowitz & Post, 1982; Leibowitz, Owens, & Post, 1982) make some further distinctions between the focal and ambient visual systems. In particular, focal operations are typically well represented in consciousness (i.e., observers tend to be aware of focal activities), while ambient functions can often operate in the absence of awareness. Also, focal vision is more adversely affected by low levels of luminance, decreased quality of the retinal image (i.e., refractive error), low spatial frequencies (which are sufficient for ambient vision), and optical rearrangement (i.e., ambient vision can adapt to prismatic reversal, while focal cannot). We

note that, although foveal and peripheral vision play important roles in focal and ambient vision, respectively, they do not characterize these channels exclusively.

Several studies have shed additional light on the focal-ambient distinction and demonstrated the ability of observers and drivers to time-share focal and ambient tasks with measurable success.

### Experimental Findings

Wickens (1986) noted that declines in tracking performance when displays are separated may be due to the loss of acuity or resolution when one task falls in peripheral vision, interference from competition over processing resources, or interference from configuration or orientation of displays. In general, tracking performance is degraded with more peripheral displays (Allen, Clement, & Jex, 1969; Levison, Elkin, & Ward, 1971; Moss, 1964). For example, Allen et al. (1969) used highly separated (i.e., 30°) tracking tasks. Participants did their best to manually track both displays under different viewing conditions, including (a) natural scanning conditions, (b) natural scan with a blanking of the peripheral task, (c) natural scan with peripheral blanking and foveal blanking 0.25 seconds after fixation, and (d) no scan, while focused on one of the two displays. As expected, performance on a given task was best when fixated directly; there was a four-fold increase in tracking error when it was performed peripherally (i.e., in the absence of scanning). However, when scanning was permitted there were costs to performance when the operators were deprived of primary display information normally available from peripheral vision—that is, when the peripheral display was blanked, performance was worse than when this information was available.

These results suggest that there is some degree of parallel processing between focal and ambient resources during the concurrent tracking tasks, especially when observers are actively scanning between displays. (The generally poor tracking performance when the tasks were viewed peripherally may be due to the displays used, which were geared towards foveal vision (i.e., requiring some degree of discrimination) and were probably not well-suited to ambient visual resources.) In contrast to the findings reported by Allen et al. (1969), Tsimhoni and Green (2001) found that peripheral viewing of a primary tracking task (i.e., driving) did not benefit performance for this task compared to conditions where the unattended primary task was completely occluded, suggesting that, in this case, ambient resources were not using the peripheral information effectively.

Levison et al (1971) showed that visual fields might be asymmetrical in nature, such that the direction of display separation may impact the degree to which two tasks can be performed concurrently. In their study, they showed that primary tracking performance was best when participants fixated up and to the right of the primary task (i.e., when the peripheral task was down and to the left in the visual field). This finding is consistent with Previc's (1998, 2000) notion that ambient vision is lower-field dominant. Sochacki and Wickens (1997) replicated the trend for tracking to be better performed in the lower than the upper visual field in a dual task configuration.

Weinstein and Wickens (1992) sought to explore the multiple resource theory implication of the focal-ambient distinction. In their study, pilots performed centrally or peripherally located side tasks while engaged in a concurrent compensatory tracking task. The tracking task was presented on one of three types of displays—each presenting different degrees of pertinent central and / or peripheral information. Side tasks were either motion-judgment (ambient resources) or object-recognition (requiring focal resources), which were presented at low luminance to ensure that focal vision would be required to discriminate the targets and with constrained time courses to ensure that observers would not have sufficient time to fixate the targets in peripheral side task conditions. In general, the pilots tended to protect the tracking task, with decrements showing up in side task performance (e.g., Horrey & Wickens, 2002).

Their results suggest that two peripherally located tasks were found to interfere more than one central and one peripheral task, or two central tasks (which offered the best performance). However, peripheral tasks that drew upon ambient resources (motion-judgment) showed smaller decrements in dual-task conditions than peripheral tasks requiring focal vision (object-recognition). In general, tasks were found to be more demanding when presented peripherally, compared to when they are presented centrally (thus, peripheral processing of information is not resource-free). Overall, there was some support for separate visual channels although this support was, in general, subject to several qualifications. Thus, no clear evidence was shown to support the separate resource aspects of focal and ambient visual channels though this may be a function of the side tasks that were used. It is possible that the ambient, motion-judgment task still relied to a certain degree on focal resources because it occupied only a small portion of the display. Ambient vision, therefore, may be best expressed through more global tasks involving orientation, postural control and ego-motion control of flow fields (Previc, 1998, 2000), as opposed to discriminating non-egocentric motion.

We note some work by Summala colleagues that can be interpreted within the focal-ambient framework. For example, Summala, Nieminen, and Punto (1996; also Summala, 1998) showed that some driving tasks might be performed effectively while using only peripheral vision. Using a “forced peripheral driving” paradigm, drivers were instructed to focus their visual attention on an in-vehicle display and avoid scanning to and from the roadway. (Eye movements were monitored to assure that scanning did not take place.) Thus, drivers were instructed to complete the driving task using their peripheral vision alone (similar to Allen et al., 1969). Secondary display locations were located either 7° below the horizon line (on top of the vehicle dash), 23° from the horizon line (beside the conventional speedometer display), or 38° from the horizon (near the mid-console of the vehicle). Driving performance was assessed by the distance of a course that drivers completed prior to departing from their lane. Lane keeping ability declined with increasing display separation however drivers were still able to complete a good portion of the test course (~80-90%), even with the larger display separations. This suggests that, on this relatively easy course, drivers were able to draw upon ambient visual resources in order to main-

tain vehicle control. Experienced drivers showed better performance than novices using the more eccentric displays, suggesting that the use of peripheral (ambient) vision may be a practiced skill (e.g., Mourant & Rockwell, 1970, 1972). In the Summala studies, performance tradeoffs were not examined, nor was there any assessment of performance on the side task when fixated centrally in the driving environment (i.e., using ambient resources to compete the IVT task). Hazard detection was also not assessed.

However, in subsequent experiments Summala, Lamble, and Laakso (1998; also Lamble, Laakso, & Summala, 1999) did explore hazards and showed that ambient vision, though effective for vehicle control, did not support the important driving task of hazard awareness. Using the same forced peripheral technique as Summala et al. (1996), they measured drivers’ response times to a braking lead vehicle. The results showed that response times increased markedly with increasing display eccentricities (losses of about 2.9 seconds compared to baseline conditions). Performance did not improve with experience, suggesting that ambient vision cannot support the more focal task of hazard detection even as it can be expanded (with learning) to better support vehicle control (Summala et al., 1996).

Collectively, these studies can be interpreted to suggest that ambient vision can support some aspects of the driving task, vehicle control in particular (Summala et al, 1996), though this ability does decline as display separation becomes excessive. When using ambient vision, it would be assumed that the driver would not need to scan upward while processing the IVT at a head down location. In contrast, hazard awareness cannot be entirely supported by ambient vision at the same eccentricities, because this task relies on focal vision.

### Visual Scanning

While there may be evidence for some contribution of focal and ambient visual resources in driving tasks, there is also a body of literature examining drivers’ overt scanning behavior while engaged in in-vehicle tasks. For example, Wierwille (1993) describes a deterministic model of in-vehicle sampling behavior in which visual scanning is regulated by the amount of time required to extract information from an in-vehicle display. In general, this model posits that if the display task cannot be completed in approximately 1.6 seconds, the driver will return his or her eyes to the roadway momentarily before refocusing on the IVT display. This cycle continues until the IVT task is completed or abandoned by the driver. The glance duration used in this model (1.6 s) is based on scan data for a number of traditional in-vehicle systems and controls (e.g., speedometer, climate control gauges; Dingus, Antin, Hulse, & Wierwille, 1989).

Consistent with this model, Gellatly and Kleiss (2000) showed that glance durations were relatively stable (at about 1 second) across IVT tasks of varying complexity, while the number of glances and the task completion times increased with complexity. This strategy however, if and when adopted, is not infallible—Wierwille and Tijerina (1998) documented the relationship between increased in-vehicle demands (from various systems) and accident occurrence. Using data from a

literature review on the frequency of system use and accident statistics, the authors established a positive correlation between the visual demands of an in-vehicle system and accident risk.

Hada (1994) explored the impact of different in-vehicle display locations on visual scanning behavior. In this study, drivers were instructed to fixate on a small visual target, positioned in a HUD location (slightly below drivers' frontal view, 7° below line-of-sight) or a location near the top of the center console (e.g., a HDD, 12° down and 30° offset), for as long as and as often as they felt comfortable. In general, the mean glance duration was slightly, but significantly longer with the HUD location (1.1 s) than for the HDD location (1 s) and these durations tended to be longer on an expressway than on rural and suburban roads. Drivers, in both conditions, spent an equivalent proportion of time looking at the display. We note however that drivers were not completing any task at the different locations, nor were they accessing any information. As such, the presence of these elements (i.e., IVT task demands or relevant information) may impact scan patterns to these display locations differentially.

Tsimhoni and Green (2001) provide a nice examination of the visual demands of an IVT map display of different levels of complexity and the impact on driving performance with roads of varying degrees of difficulty (curvature). The results showed that the addition of the secondary IVT task was detrimental to driving performance, with increased lane deviations and more frequent lane departures. However, as the visual demand of driving increased (i.e., sharper curves), drivers made shorter glances to the IVT and took longer in between consecutive glances to the IVT (i.e., while fixating the roadway), though there was an increase in the total number of IVT glances, yielding longer IVT completion time. Consistent with the Wierwille model, these downward glances approximated 1.8 second durations on straight road sections and 1.2 second duration on curved sections. Overall, there was very little change in IVT completion time as the visual demand of driving increased, however there was a degradation of driving performance (even in spite of a reduction in the amount of time with the eyes-off-the-road). The authors suggest this as evidence that risk homeostasis is not maintained—or, in other words, drivers were not adequately protecting the driving task from degradation.

In another examination of IVTs, Lansdown (2002) evaluated the visual allocation of drivers engaged in a secondary in-vehicle task of various degrees of complexity. Drivers drove through a simulated traffic environment while performing a task on an in-car entertainment (ICE) system located in the central dashboard console. There were three different levels of complexity for the in-vehicle task, involving varying degrees of user interaction. As side task complexity increased, so did the total amount of time spent looking at the display and the number of fixations towards the display. Furthermore, the mean glance duration to the ICE system across various task complexities ranged from 0.5 to 1.6 seconds, an upper limit consistent with the Wierwille model. Lansdown & Fowkes (1998) report similar findings in another examination of IVTs of increasing complexity, though they further report increased

glance durations from 0.9 to 1.1 seconds with the most complex system.

Thus in general, scan research suggests some consistency in the maximum 1.5 to 2 sec maximum head down glance duration, although this value appears to be somewhat modulated by task demands. However, the reported values are means, whereas accidental neglect may be attributed to the longest values in the tails of the distribution. Furthermore, this research generally fails to address two factors important in visual attention allocation within the vehicle: the modulating role of vehicle speed, and the external “event rate” of hazardous events that could leave the driver vulnerable to accidents during head down glances. To what extent are driver glance durations insulated from variations in these sources, to preserve constant risk? We propose two versions of a model that can make predictions regarding this insulation from (or sensitivity to) risk factors; one based on pure visual single channel theory, and the other based on single channel focal vision and dual channel ambient vision.

### Proposed Models

The pure *single channel model* extends work of Moray (1986) and Senders (1983) as well as that of Wierwille and Tijerina (1998). According to this model, vision will either be on the roadway or the IVT, but not both. Therefore, the accident risk vulnerability might be characterized by Equation 1:

$$AccidentRisk = MDD_{IVT} \times EventRate \quad (1)$$

where  $MDD_{IVT}$  is the mean dwell duration of IVT glances (the value estimated by Wierwille (1993) to be 1.6 sec), and *Event Rate* represents the frequency of relevant road events (expressed as *road event rate* (events/km) x *velocity* (km/second)). Road events can be classified into two categories: *collision events* (ColEvent), involving potential collisions with on-road objects (e.g., pedestrians, other vehicles), and *control events*, which characterize the required lane displacement inputs of a standard tracking task. These control events arise from three sources: road curvature, turbulence, and the drivers' own steering activity. From these sources, the event rate for road curvature is a function of curve density and vehicle speed. In contrast, turbulence event rate is unaffected by speed and so is just equal to the absolute turbulence bandwidth. Steering event rate refers to that steering activity generated by inadvertent “internal noise” or “remnant” (Wickens, 1986; McRuer, 1980), and its contributions are assumed to be proportionally greater at higher speeds. We have, therefore, four parameters that are moderated by vehicle velocity and one, turbulence, that is not. Equation 1 can be modified appropriately to yield:

$$AccRisk = MDD_{IVT} \times [(ColEvent + Curve + Steer) \times Vel + Turb] \quad (2)$$

where *ColEvent* (collision events) and *Curve* are defined in terms of density per unit distance, *Steer* is a constant (whose impact is proportional to velocity) and *Turb* is expressed in perturbations per second. *Vel* is the vehicle velocity.

While this single channel model cannot be expected to precisely predict accident frequency, it can be used to test the extent to which downward glance durations are sensitive or

insensitive to changes in the parameters. Furthermore, the visual single channel model predicts that all four variables will influence glance duration. However, the *dual channel (focal ambient) model* will predict an influence **only** of collision events, the first parameter, on scan dwells as it is assumed that the driver can process and respond to the tracking events using the upper peripheral visual field.

Naturally, we believe that driver behavior is often a mixture of these two models, becoming more like pure single channel as an IVT is displaced further downward, and as outside visibility is decreased.

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## REFERENCES

- Allen, R.W., Clement, W.F., & Jex, H.R. (1969). *Research on display scanning, sampling, and reconstruction using separate main and secondary tracking tasks* (Tech Report 170-2). Moffett Field, CA: National Aeronautics and Space Administration.
- Dingus, T.A., Antin, J.F., Hulse, M.C., & Wierwille, W.W. (1989). Attentional demand requirements of an automobile moving-map navigation system. *Transportation Research*, 23A(4), 301-315.
- Gellatly, A.W. & Kleiss, J.A. (2000). Visual attention demand evaluation of conventional and multifunction in-vehicle information systems. *Proceedings of the IEA 2000/HFES 2000 Congress* (pp. 3:282-3:285). Santa Monica, CA: Human Factors and Ergonomics Society.
- Hada, H. (1994). *Drivers' visual attention to in-vehicle displays: Effects of display location and road type* (Tech Report UMTRI-94-9). Ann Arbor, MI: University of Michigan, Transportation Research Institute.
- Horrey, W.J. & Wickens, C.D. (2002). *Driving and side task performance: The effects of display clutter, separation, and modality* (Tech Report AHFD-02-13/GM-02-2). Savoy, IL: University of Illinois, Aviation Human Factors Division.
- Horrey, W.J., Alexander, A.L., & Wickens, C.D. (2003). *Does workload modulate the effects of in-vehicle display location on concurrent driving performance?* (Tech Report AHFD-03-1/GM-03-1). Savoy, IL: University of Illinois, Aviation Human Factors Division.
- Lamble, D., Laakso, M., & Summala, H. (1999). Detection thresholds in car following situations and peripheral vision: Implications for positioning of visually demanding in-car displays. *Ergonomics*, 42(6), 807-815.
- Lansdown, T.C. (2002). Individual differences during driver secondary task performance: Verbal protocol and visual allocation findings. *Accident Analysis and Prevention*, 34, 655-662.
- Lansdown, T.C. & Fowkes, M. (1998). An investigation into the utility of various metrics for the evaluation of driver information systems. In A.G. Gale et al. (Eds.), *Vision in vehicles – VI* (pp. 215-224). Amsterdam: Elsevier.
- Leibowitz, H.W., Owens, D.A., & Post, R.B. (1982). *Nighttime driving and visual degradation* (SAE Tech Paper #820414). Warrendale, PA: Society for Automotive Engineering.
- Leibowitz, H.W. & Post, R.B. (1982). The two modes of processing concept and some implications. In J. Beck (Ed.), *Organization and representation in perception* (pp. 343-363). Hillsdale, NJ: Lawrence Erlbaum.
- Levison, W.H., Elkind, J.I., & Ward, J.L. (1971). *Studies of multi-variable manual control systems: A model for task interference* (Tech Report NASA CR-1746). Washington, DC: NASA.
- McRuer, D.T. (1980). Human dynamics in man-machine systems. *Automatica*, 16, 237-253.
- Moray, N. (1986). Monitoring behavior and supervisory control. In K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 2) (pp. 40.1-40.51). New York: John Wiley & Sons.
- Moss, S.M. (1964). Tracking with a differential brightness display: II. Peripheral Tracking. *Journal of Applied Psychology*, 48, 249-254.
- Mourant, R.R. & Rockwell, T.H. (1970). Mapping eye-movement patterns to the visual scene in driving: An exploratory study. *Human Factors*, 12(1), 81-87.
- Mourant, R.R. & Rockwell, T.H. (1972). Strategies of visual search by novice and experienced drivers. *Human Factors*, 14(4), 325-335.
- Previc, F.H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin*, 124(2), 123-164.
- Previc, F.H. (2000). Neuropsychological guidelines for aircraft control stations. *IEEE Engineering in Medicine and Biology*, March/April, 81-88.
- Senders, J.W. (1983). *Visual sampling processes*. Hillsdale, NJ: Erlbaum.
- Sochacki, J. & Wickens, C.D. (1997). *Display location and task-hemispheric integrity effects on HUD display designs* (Tech Report ARL-97-2/FAA-97-2). Savoy, IL: University of Illinois, Aviation Research Laboratory.
- Summala, H. (1998). Forced peripheral vision driving paradigm: Evidence for the hypothesis that car drivers learn to keep in lane with peripheral vision. In A.G. Gale et al. (Eds.), *Vision in vehicles – VI* (pp. 51-60). Amsterdam: Elsevier.
- Summala, H., Lamble, D., & Laakso, M. (1998). Driving experience and perception of the lead car's braking when looking at in-car targets. *Accident Analysis and Prevention*, 30(4), 401-407.
- Summala, H., Nieminen, T., & Punto, M. (1996). Maintaining lane position with peripheral vision during in-vehicle tasks. *Human Factors*, 38(3), 442-451.
- Tsimhoni, O. & Green, P. (2001). Visual demands of driving and the execution of display-intensive in-vehicle tasks. *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting* (pp. 1586-1590). Santa Monica, CA: Human Factors and Ergonomics Society.
- Wickens, C.D. (1986). The effects of control dynamics on performance. In K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 2) (pp. 39.1-39.60). New York: John Wiley & Sons.
- Wickens, C.D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, 3(2), 159-177.
- Weinstein, L.F. & Wickens, C.D. (1992). Use of nontraditional flight displays for the reduction of central visual overload in the cockpit. *International Journal of Aviation Psychology*, 2(2), 121-142.
- Wierwille, W.W. (1993). Visual and manual demands of in-car controls and displays. In B. Peacock & W. Karwowski (Eds.), *Automotive Ergonomics* (pp. 299-320). Washington, DC: Taylor & Francis.
- Wierwille, W.W. & Tijerina, L. (1998). Modelling the relationship between driver in-vehicle visual demands and accident occurrence. In A.G. Gale et al. (Eds.), *Vision in vehicles – VI* (pp. 233-243). Amsterdam: Elsevier.